Hyperloop

A Multi-Objective Optimization Approach to Network Design

MSc Thesis

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TUDelft

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by

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Preface

Dear Reader,

The report you're holding right now is more than just a collection of pages. It's the culmination of my journey through the master's programme in Complex Systems Engineering and Management (CoSEM) at Delft University of Technology. As I glance at these words, I'm reminded that this study isn't just the conclusion of my research; it's also the closing of a cherished chapter of my life at TU Delft. These pages symbolize the countless hours of hard work, late nights, and moments of inspiration that have shaped not only my academic path but also who I've become. Undoubtedly, this research would not have been possible without the guidance of my supervisor, Yousef Maknoon. I would like to express my gratitude for your help and inspiration throughout the entire process. Your guidance and expertise have led me to a research topic that enabled me to work on a study where I had to combine all of my academic knowledge which fulfilled me greatly. Second, I would like to thank my second supervisor Petra Heijnen. Your critical approach and the alternative view you have provided me with enriched the output of my research and helped me garner wisdom from different disciplines. Third, I would like to thank Jafar Rezeai for his critical view and curiosity on the subject. Your contributions have always helped me see the big picture and put things in perspective which is in alignment with the essence of the CoSEM programme.

Furthermore, I would like to thank my family who have sacrificed so much from their own lives for me to be able to live out my own dreams. Throughout my academic career, they have always supported me no matter the obstacle and encouraged me to forge my own path. I owe them a debt of gratitude that can never truly be repaid for their unconditional love. To my friends, who have been my pillars of strength and a source of laughter and encouragement, your presence in my life has made these moments unforgettable, and I'm immensely thankful for the memories we've created together. A special thank you goes to my beautiful girlfriend, Irmak. Thank you for always inspiring me with your dedication and being there for me when I needed it the most.

It's bittersweet to see this phase come to an end, but I'm also excited about the new horizons ahead. As I prepare to embark on new adventures, I can't help but reflect on the incredible experiences I've had here, moments that have left an indelible mark on my heart. Looking back, I'm overwhelmed with a mix of pride and joy. The growth I've undergone, both academically and personally, is beyond what I could have imagined. Words fail to capture the depth of my gratitude for the opportunities I've had and the friendships I've formed.

Doruk Ergez
Delft, August 2023

Summary

The pivotal sector of transportation has shown signs of a surge in demand. The European Union projects a 42% increase in passenger transport from 2019 until 2050 [25]. Policymakers and stakeholders must collaborate to address the increasing transportation demand while considering environmental, societal, and economic benefits. Specifically, the transportation sector contributes significantly to greenhouse gas emissions and environmental challenges. Despite efforts to mitigate emissions, the transportation sector has not achieved substantial reductions. The projected increase in transportation demand exacerbates the issue, requiring urgent action to meet carbon neutrality goals. Rail transport emerges as a sustainable alternative, with potential modal shifts from aviation and road transport. However, the expansion of rail networks and infrastructure faces challenges in terms of funding and integration with other modes of transport. Policy interventions show potential in increasing the modal share of rail, but additional measures are necessary to reduce reliance on air travel. The emergence of Hyperloop technology presents a disruptive solution that could address this transportation challenge in Europe. The Hyperloop is an innovative mode of transportation that has garnered attention within the transportation industry over the past decade. It has been pursued as a viable alternative to air travel, rail, and traditional forms of transportation due to its affordability, sustainability, and rapid speeds of up to 1200 km/h. Even though Hyperloop is a promising alternative in the transportation sector, the technology is still largely in development. There are multi-dimensional considerations in understanding whether the Hyperloop will become a mainstream transport option for passengers and whether the conflicting objectives will result in an efficient Hyperloop network. A knowledge gap was identified with a lack of studies to explore the relationship between the network design objectives and the network design itself.

In order to identify the impacts of the Hyperloop network design in the global transportation sector, a literature review was conducted on the transformative potential of the Hyperloop. Key strengths were identified as a reduction in travel times and low operational emissions. On the other hand, the high capital resources required and the uncertainty around the safety of technology were the main points of criticism. In order to analyze the potential demand for Hyperloop and model the modal shift, a Multi-Nominal Logit was employed where a utility function was formulated for the total benefit passengers receive upon completing a trip. The key attributes for the utility function were selected as travel time, travel costs, number of transfers, and safety perception, in alignment with previous studies on the subjects. A utility-based probabilistic mode choice was determined for the available demand. A multi-objective optimization problem was formulated for the facility-location network design of Hyperloop. The decision variables of the model were formulated as the decision to open a Hyperloop hub at a location and the decision to build infrastructure between the selected Hyperloop hubs. The model output is an alternate network optimized for four different objective functions. These objectives are determined to be (1) Utility Maximization, (2) Probability of Purchase Maximization, (3) Emission Minimization, and (4) Revenue Maximization as these factors were determined to be key performance indicators in a prospective Hyperloop network. The model aims to provide the decision-makers with an overview of the trade-offs involved with varying objective criteria considered in the network generation.

A case study was created to test the model within Europe. The main aim of the case study is to assess the economic and environmental impacts of the Hyperloop system and provide recommendations to policymakers regarding the conception of the Hyperloop network within the European Union. The case study employs the NUTS classification and excludes European countries where the demand data is incomplete and focuses on countries within the TEN-T network. Furthermore, three categories of experimental scenarios were set up to assess the sensitivity of the model to parameter values. The categories are (1) pricing strategy scenarios, (2) safety perception scenarios and (3) policy intervention scenarios. The findings reveal significant disparities in network characteristics based on different objective criteria. The Utility Maximization objective focuses on maximizing trip utility, leading to a network design with direct links between hubs, resulting in compact networks and lower infrastructure costs.

However, Spain and Italy have lower priority in this design. On the other hand, the other three objectives (probability of purchase maximization, emission minimization, and revenue maximization) yield networks with a minimum-spanning tree pattern. These networks outperform the utility maximization network in terms of attracting passengers, reducing emissions, and economic performance. To maximize societal benefits, it is recommended to prioritize the remaining three objectives. The study finds that Hyperloop becomes more competitive for longer-distance trips. Experimentation with ticket prices, safety perception, and policy interventions demonstrates their influence on modal share, revenue stability, and carbon emissions. Higher ticket prices discourage Hyperloop usage, safety perception plays a crucial role, and policies discouraging short-haul flights result in higher Hyperloop modal share and lower emissions. These findings highlight the importance of considering ticket prices, safety perception, and strategic policies to promote sustainable transportation and reduce carbon emissions through a modal shift to Hyperloop.

Future research opportunities include expanding the utility function to incorporate additional attributes affecting mode choices, exploring modal shifts from other modes to Hyperloop, relaxing assumptions about geographical obstacles and hub locations, integrating strategic and tactical planning, and validating the model with a broader range of origin-destination pairs. Computational performance can be enhanced using meta-heuristics to compare different heuristics for network outputs and efficiency.

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Nomenclature

Abbreviations

Abbreviation	Definition
EC	European Commission
EEA	European Environment Agency
EU	European Union
GDP	Gross-Domestic Product
GHG	Green-house gases
Gpkm	Giga passenger-kilometers
HSR	High-Speed Rail
HST	High-Speed Train
LIM	Linear Induction Motor
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Non-Linear Programming
MNL	Multi-nominal Logit
Mpg	Miles per Gallon
MW	Megawatt
NUTS	Nomenclature of Territorial Units for Statistics
RUM	Random-Utility Model
TEN-T	Trans-European Transport Network

1 Research Introduction

1.1. Growing Passenger Transport Demand in Europe

The transportation sector assumes a pivotal position within our society, holding significant influence in connecting individuals to essential services, activities, and cultures that contribute to their well-being and the overall economy. From the conveyance of goods to the facilitation of human mobility, the transportation sector stands as a fundamental pillar within any given economy. It enables access to vital resources and services while fostering global interactions. In the European Union, the transportation sector provides essential freedom of movement for citizens and accounts for 5% of the entire GDP of the region [26].

Nevertheless, transportation encompasses more than the mere movement of goods and people; it represents a complex issue that is subject to various factors, yielding both positive and negative consequences for society. The escalating demand for transportation within Europe has emerged as a pressing concern, demanding immediate attention from policymakers and stakeholders. As populations continue to grow and urbanization intensifies, transportation activities are expected to expand correspondingly. Notably, the European Union projects a 36% surge in total passenger kilometers between 2015 and 2050 [24]. This trend is expected to continue for both passenger and freight transport, as future projections estimate a 42% increase in total passenger transport until 2050 compared to 2019. The scenario is even more dramatic for freight transport. European Union expects a 60% increase in total freight transport activities until 2050 compared to 2019 [25]. The rest of this document will be focused on passenger transport in Europe in line with the scope of the research.

The anticipated surge in transport volume is deemed advantageous in terms of economic growth and trade [25]. However, it is uncertain whether the existing transport infrastructure possesses the requisite capacity to effectively accommodate this pronounced upturn. The introduction of novel technologies and technical innovations poses challenges to the incumbent transport infrastructure, as the integration of these emerging technologies is often intricate, and their intricate societal implications remain shrouded in ambiguity [77]. Such implications are often split into three categories of direct,indirect and cumulative impacts [107]. Direct impacts are those that have an immediate consequence on the society such as land-use changes as a result of a new station being built [127]. Indirect impacts are related to the consequences of transport activities. One such example could be the waste disposal problems associated with public transport usage [77]. Cumulative impacts are additive effects on society such as the health and well-being of transport system users [126]. In order to avoid a sub-optimal transportation system, the challenges that lie ahead within the context of the increasing transport demand must be analyzed in a comprehensive manner.

1.2. Transport Challenges in Europe

The escalating demand for transportation within Europe necessitates a comprehensive comprehension of the underlying factors. It is imperative for policymakers and stakeholders to engage in collaborative endeavors aimed at implementing sustainable strategies that reconcile environmental, societal, and economic benefits [15]. Effectively addressing the mounting transportation demand in Europe mandates a multifaceted approach that necessitates a holistic understanding of the multifarious impacts of transportation on society, the environment, and the economy. In order to ensure an efficient, safe, clean, and accessible transport network, accurate policy interventions at both national and European levels must be employed to mitigate negative externalities. The European Commission has recently published its smart and sustainable mobility strategy, wherein they identify several critical obstacles, namely sustainability, connectivity, multi-modality, and congestion [25].

1.2.1. Sustainability and Environmental Consequences

The European Union has made a significant commitment to becoming the world's first carbon-neutral continent, aiming to achieve net-zero greenhouse gas emissions by 2050 [23]. This commitment is reflected in the European Green Deal [31], a comprehensive policy framework that seeks to facilitate a sustainable transformation of the European economy and industry in alignment with the objectives set forth in the 2015 Paris Agreement [119].

It is essential to recognize the substantial contribution of the transportation sector to greenhouse gas emissions, which in turn gives rise to various environmental challenges, including climate change, air pollution, and the depletion of natural resources. According to reports from the European Environment Agency, the transportation sector accounted for more than a quarter of the total greenhouse gas emissions in the European Union in 2020, as depicted in Figure 1.1.

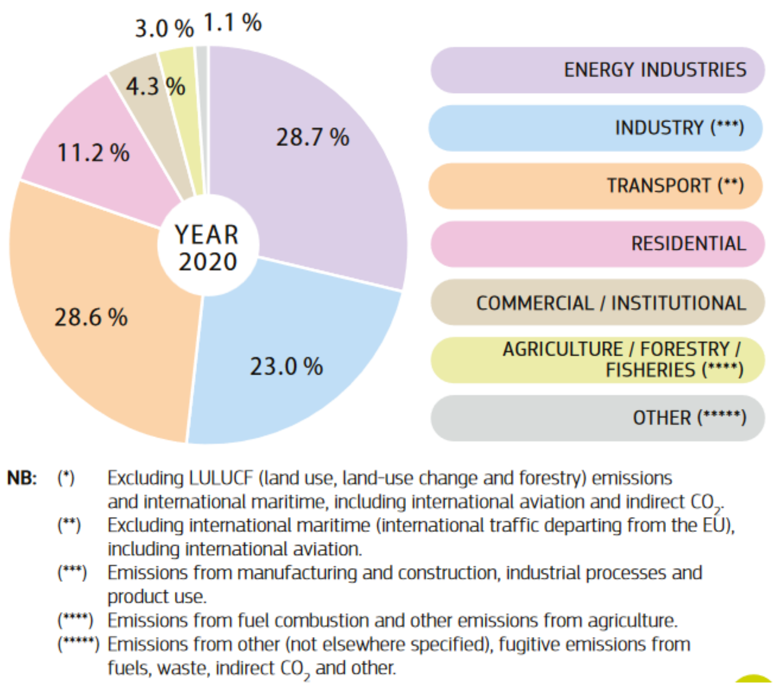

Figure 1.1: Greenhouse Gas Emission per Industry in 2020. Source: European Environment Agency

When analyzing the historical greenhouse gas emissions across various sectors, it becomes apparent that the transportation sector stands out as a notable contributor. Specifically, considering the reference year established by the European Union as 1990, the transportation sector exhibits a concerning trend. Despite concerted efforts to mitigate emissions and address climate change, the transportation sector has failed to achieve a significant reduction in its greenhouse gas emissions as it can be seen in Figure 1.2.

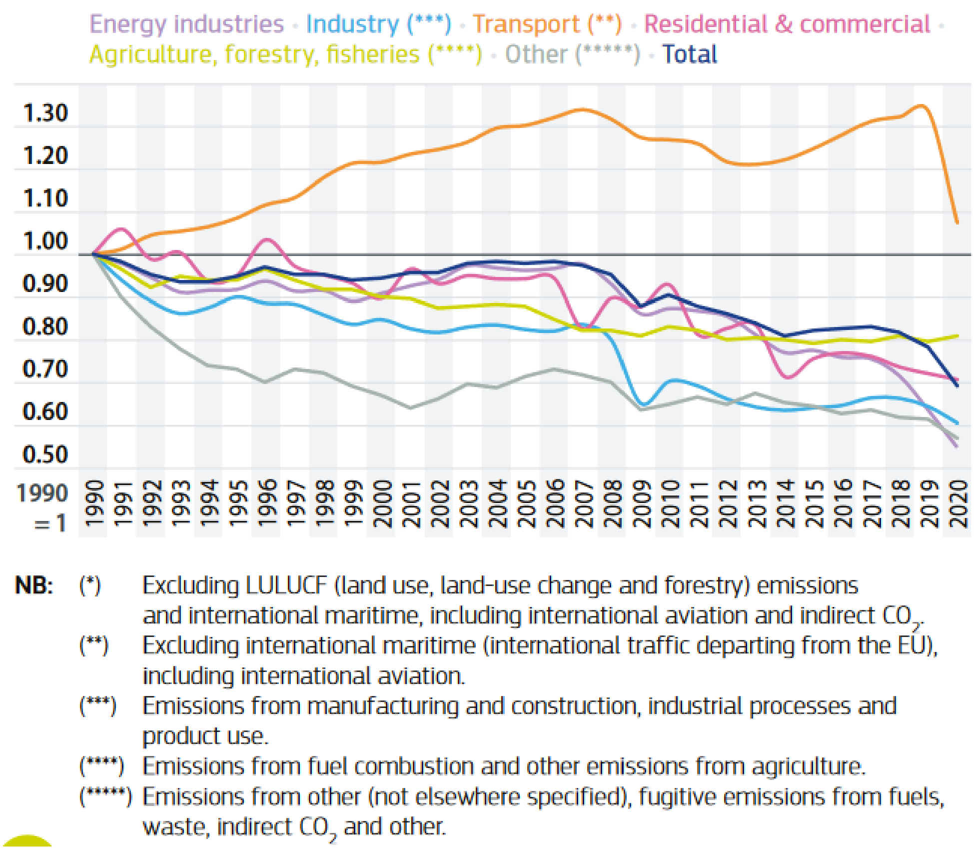

Figure 1.2: Change in Greenhouse Gas Emissions per Industry compared to 1990 in 2020. Source: European Environment Agency

This discrepancy becomes particularly pronounced when comparing the emissions trajectory of the transportation sector to that of other sectors. While significant progress has been made in curbing emissions in sectors such as energy production, manufacturing, and residential activities, the transportation sector has lagged behind in achieving commensurate emissions reductions.

As a result, the transportation sector remains the only sector that has yet to achieve a noteworthy decline in greenhouse gas emissions when comparing 2020 data to the reference year of 1990. This disparity is cause for concern as it suggests that current strategies and interventions aimed at reducing emissions within the transportation sector may not be as effective as anticipated. Of concern is the projected escalation in emissions volume, which is anticipated to surge alongside the persistent growth in transportation demand. It is worth noting that this brings forth an urgency to the issue. If the thresholds outlined by the European Green Deal are to be achieved, 90% of all emissions from the transportation sector must be completely eliminated by the year 2050 [26]. In an effort to comprehend these worrisome trends and identify crucial intervention areas, the European Commission's Directorate-General for Energy, Directorate-General for Climate Action, and Directorate-General for Mobility and Transport have undertaken an assessment of future energy, transport, and greenhouse gas (GHG) emissions scenarios up to the year 2050[24]. Through this analytical endeavor, they aim to gain insights into the potential trajectories of emissions and discern critical focal points for intervention. It is worth noting that this study also assumes that the current initiatives toward sustainable transport in the European Union are fully realized. Therefore, it serves as a good basis to verify if the current strategies are sufficient enough to reach the intended goals. The output of the projection can be found in Figure 1.3.

The findings of the aforementioned study on future projections reveal that the total passenger kilometers are poised to rebound following the impact of the COVID-19 outbreak. This resurgence underscores the critical imperative to further curtail emissions, as the anticipated surge in transport volume would result in an increase rather than a decrease in total greenhouse gas (GHG) emissions. Two primary observations emerge from these projections.

Firstly, passenger car transport is projected to persist as the predominant contributor to the overall passenger transport volume until 2050. However, it is anticipated that the relative share of passenger cars will gradually diminish over time due to an anticipated modal shift. Consequently, there is an urgent need to incentivize passengers to transition towards more sustainable modes of transport during their mobility activities. Research indicates that the most suitable option for this shift is a transition towards rail transport, which stands out as the most environmentally sustainable alternative in terms of GHG emissions per passenger kilometer. Depending on the type of GHG emission, rail is 50% to 94% less polluting. [53] Within urban settings, light rail systems can serve as viable substitutes for passenger car traffic, thereby promoting sustainable mobility. Secondly, the study highlights a substantial expected increase in the share of aviation until 2050. Specifically, the intra-European Union (EU) aviation share is projected to rise from 8% in 2015 to 12% by 2050. This growth underscores the escalating significance of aviation as a contributor to the overall transport sector's GHG emissions. The projection of increased aviation usage is consistent with previous studies indicating that people shift towards faster modes of transport as their income increases [105]. This leads to higher shares of faster modes such as airplanes which are naturally more energy intensive [108]. As such, it becomes imperative to address the environmental implications of this expansion and develop effective strategies to mitigate the associated emissions [97].

The situation becomes increasingly alarming when considering the aggregate energy demand per transport mode, particularly in the case of aviation [74]. Within the realm of transportation, aviation stands out as one of the most energy-intensive sectors, contributing around 2% of the entire carbon emissions [13]. Despite the study taking into account technological advancements and the ongoing trend towards more sustainable energy sources, it is projected that the efficiency gains will be insufficient to offset the escalating energy demand resulting from increased short-haul flights within the European Union [24]. The comprehensive projection of total energy demand until the year 2050 is depicted in Figure 1.4. This graphical representation provides valuable insights, underscoring the imperative to discourage passengers from relying on flights for their mobility activities. Such a measure becomes necessary to align with the ambitious targets outlined in the European Green Deal and achieve a substantial 90% reduction in emissions within the transportation sector. Addressing the energy demand associated with aviation necessitates concerted efforts to explore alternative solutions and incentivize sustainable modes of transport. While technological advancements and the incorporation of sustainable energy sources can contribute to reducing emissions, the sheer growth in air travel volumes poses a significant challenge as there exists a high correlation between transport volumes and the emissions due to the fuel demand of airplanes [68]. Therefore, proactive measures are essential to curb the reliance on short-haul flights and encourage passengers to adopt more sustainable alternatives, such as rail or other low-emission modes of transport [121]. By highlighting the pressing need to reduce energy demand in aviation and promote alternative transportation options, policymakers can steer the industry towards more sustainable practices. In doing so, they can align with the objectives of the European Green Deal and work towards achieving the substantial emission reductions required to foster a greener and more environmentally conscious transportation sector.

When examining the array of alternative transport modes, rail emerges as a compelling choice, particularly when the objective is to minimize emissions stemming from operational activities [50]. This notion is further supported by future projections of energy demand in the transport sector, which consistently indicate that rail transport exhibits the lowest energy requirements up until the year 2050. Figure 1.4 visually portrays this trend, elucidating the favorable position of rail transport in terms of energy demand. Considering the historical development of GHG emissions of the widespread transport nodes, rail is one of the few modes of transport that has experienced a decline in emissions [46].

The preference for rail as a sustainable transport mode can be attributed to several factors. Firstly, rail systems typically employ efficient electric propulsion systems, which enable a significant reduction in greenhouse gas emissions compared to modes reliant on internal combustion engines. Moreover, advancements in rail technology, such as regenerative braking and improved aerodynamics, contribute to increased energy efficiency and further mitigate environmental impacts [54]. The consistent prominence of rail as a low-energy-demand option underscores its potential as a sustainable option in the transportation landscape. By expanding the infrastructure and optimizing rail networks, policymakers can foster modal shifts to High-Speed Rail from more energy-intensive aviation [60]. However, there are also negative externalities for expanding a rail network in both urban and suburban settings which will be discussed in the following subsection.

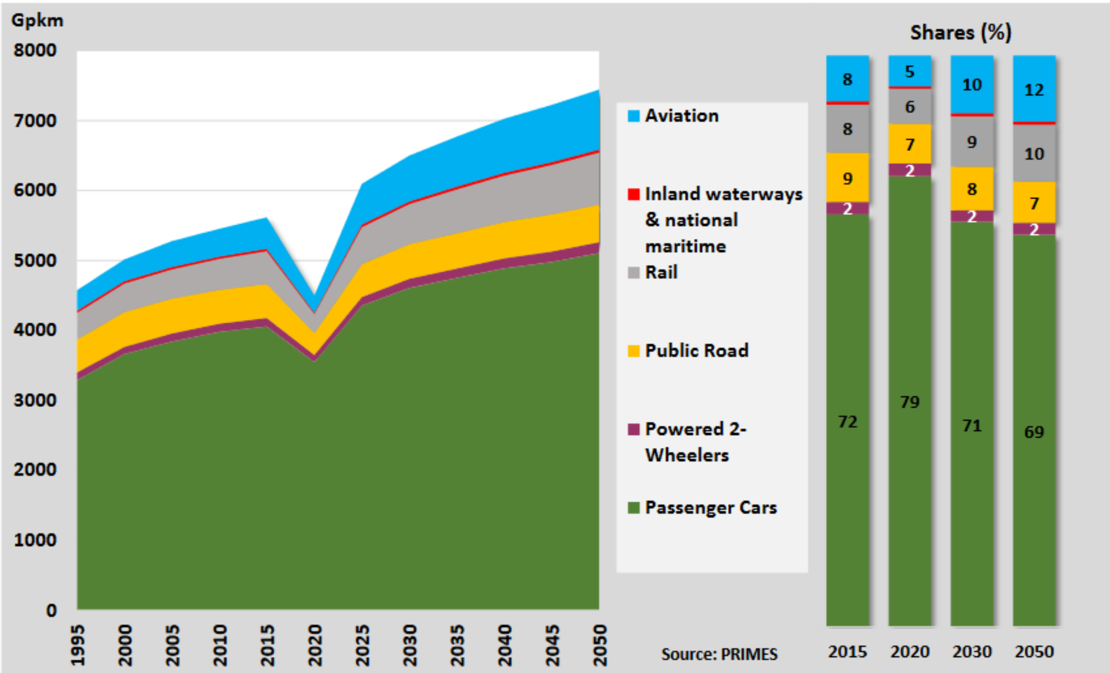

Figure 1.3: Future Projections of Total Passenger Transport Volume per mode and their shares. Source: [24]

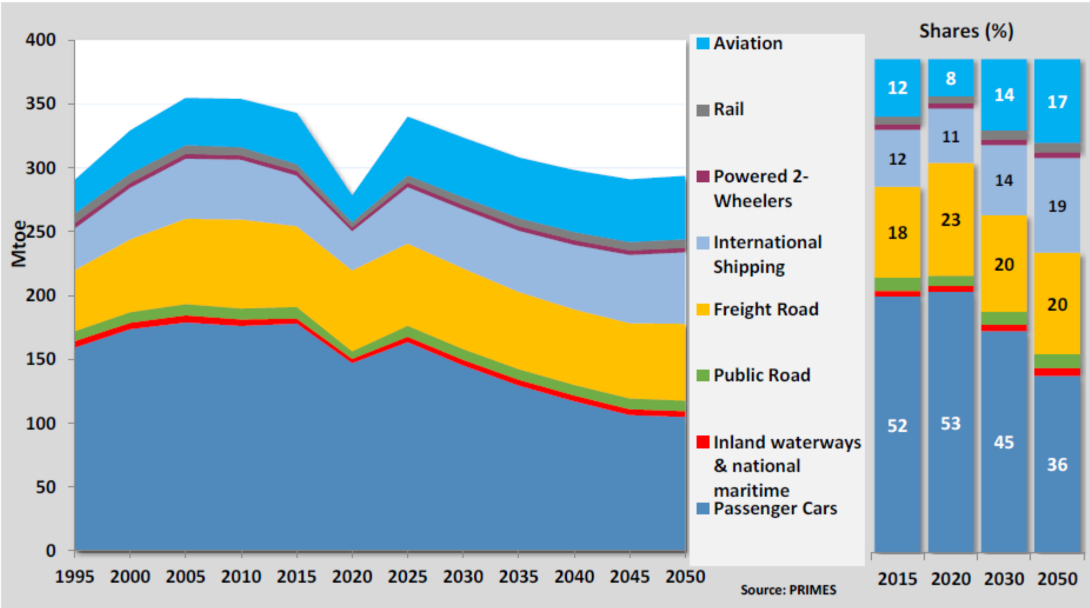

Figure 1.4: Future Projections of Total Energy Demand in Transport per mode and their shares. Source: [24]

1.2.2. Rail as an Alternative and TEN-T policy

The commendable sustainable attributes of rail transportation have garnered attention from national and international entities alike. Numerous initiatives are already underway, aiming to promote a modal shift from aviation and road transport towards rail. The European Union, in its pursuit of more sustainable transport practices, has outlined its intentions in the European Mobility Strategy and Action Plan. Within this strategic framework, ten flagships have been identified, as detailed in the provided Appendix A, to steer the transformation towards sustainable transportation.

One of the focal points of these efforts is the enhancement of rail connectivity among European nations, along with the expansion of intra-EU rail infrastructure. Recognized as a crucial area of focus, this objective seeks to facilitate the desired modal shift. As a result of these policy interventions, the demand for rail-based transport has been steadily increasing [53]. It is evident that for passengers to alter their transportation preferences from aviation and road to rail, accessible rail-based alternatives with functioning infrastructure must be widely available [17].

Ensuring the cohesion of transport infrastructure investment is paramount for fostering seamless rail connectivity. To address this need, the European Union has introduced the Trans-European Transport Network (TEN-T) policy. This critical policy initiative aims to establish an integrated and efficient transportation network throughout the European Union. By fostering collaboration and coordination among member states, the TEN-T policy seeks to facilitate the development of a comprehensive and interconnected rail infrastructure, enabling efficient and sustainable rail transportation across the continent.

The TEN-T policy road map focuses on several key aspects to achieve its objectives. Firstly, it emphasizes the development of core network corridors, which are strategic routes connecting major economic centers and important transportation hubs within Europe. These corridors span various modes of transport, including rail, road, inland waterways, and maritime connections. By enhancing the connectivity and efficiency of these corridors, the TEN-T policy aims to promote seamless multi-modal transport and facilitate the shift towards more sustainable modes of transportation. In addition to core network corridors, the TEN-T policy places emphasis on comprehensive network coverage. This entails extending the benefits of the core network to the entire European Union, including remote and less accessible regions. By ensuring comprehensive network coverage, the policy aims to promote economic growth, social cohesion, and accessibility for all regions within Europe.

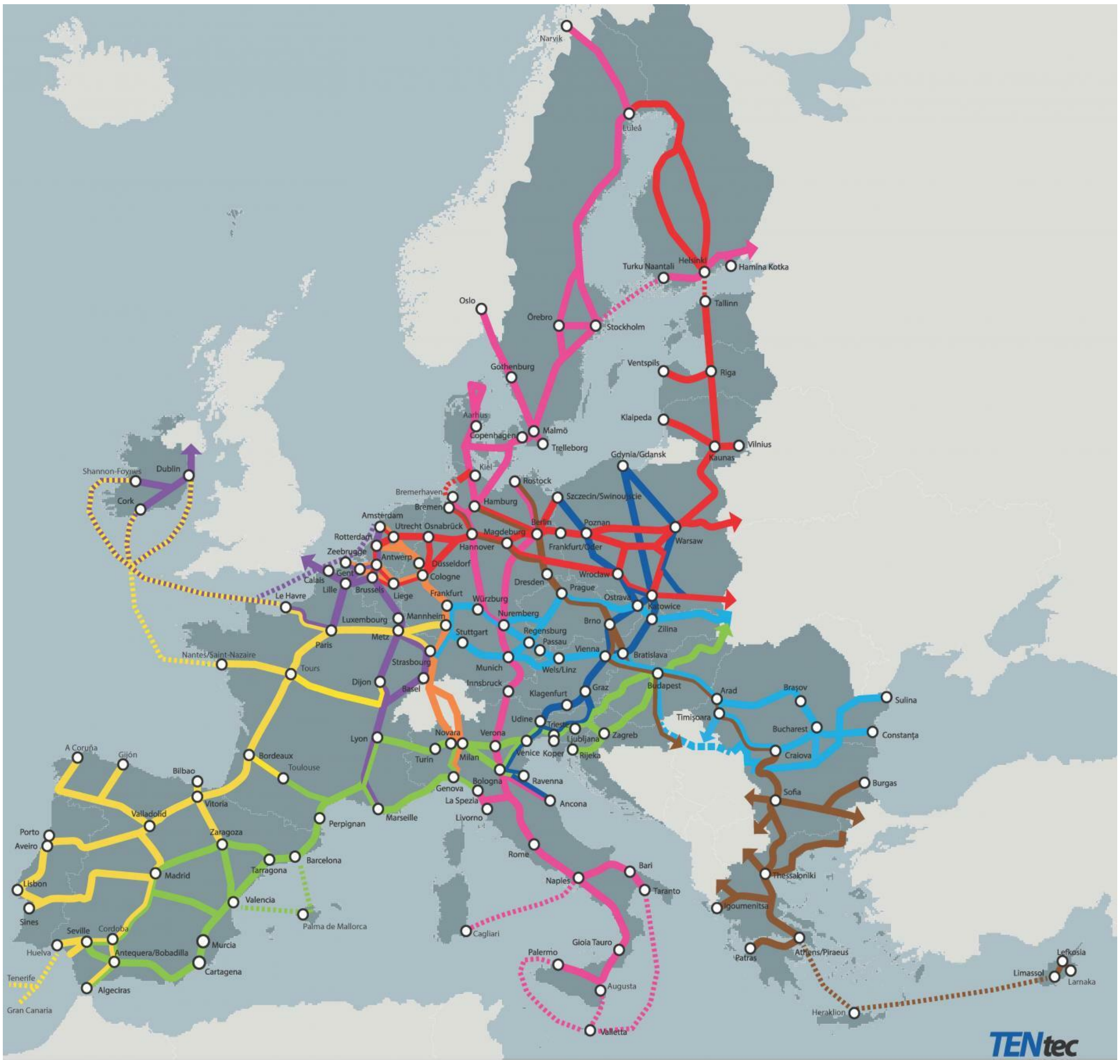

Figure 1.5: Future Projections of Total Energy Demand in Transport per mode and their shares. Source:Directorate-General for Mobility and Transport, European Commission

Similar to all network structures, full realization is vital to reap the benefits of a wide-scale modal-shift. In line with the timeline of the European Green Deal [31], TEN-T aims to complete a core network by the year 2030. The core network includes nodes of the highest strategic importance in the European Union. These include the capital city of every European Union member state, a main border crossing point between a Member State and a non-member state with the highest long-distance traffic flow, and every Metropolitan European Growth Area (MEGA) [32]. The detailed map of the regions included in the Metropolitan European Growth Area (MEGA) can be found in Appendix B. These selected nodes are to be connected in a multi-modal manner with road and rail if geographically possible. Otherwise, the nodes are to be connected by sea [32]. The policy also emphasizes that in order to be competitive with other modes of transport and to present an attractive option for passengers, the infrastructure should allow for the vehicles to be able to reach speeds of at least 160 km per hour. The visual representation of the infrastructure to be completed by the year 2030 can be found in Figure 1.5.

The implementation of the comprehensive network within the Trans-European Transportation network is a crucial step following the establishment of the Core Network. The comprehensive network expansion aims to enhance connectivity and ensure seamless transportation across all European Union member states, including those that joined after 2004. Its primary focus lies in bridging the existing gaps in infrastructure and achieving a comprehensive, multi-modal interconnection of national networks. One key objective of the comprehensive network is to address the issue of missing links within the transportation network. These missing links refer to segments or nodes that are not currently connected to the established TEN-T network at the time of implementation. The comprehensive network seeks to create a more robust and integrated European transport system by identifying and connecting these missing links. Furthermore, the comprehensive network places great emphasis on the interoperability and safety standards of rail transportation. Strict adherence to operational standards, such as rail interoperability and safety protocols, is deemed essential for ensuring a harmonized and efficient rail network across Europe. By promoting consistent operational practices and safety measures, the comprehensive network strives to enhance the overall performance and reliability of rail transport within the European Union [32].

Multi-modality plays a crucial role within the framework of the Trans-European Transport Network (TEN-T) in promoting modal shift. The implementation plan for the Core Network emphasizes the necessity for all nodes to possess multi-modal capabilities. To achieve this objective, the deployment of advanced traffic management systems becomes essential. These systems facilitate the horizontal integration and operation of existing transportation infrastructure with more sustainable alternatives, enabling seamless transfers between different modes of transport [32]. Creating an EU-wide rail network that allows for smooth transitions to more sustainable modes of transport is of paramount importance. Passengers are more likely to choose this route only if they perceive the benefits of sustainable alternatives to outweigh any inconveniences or costs associated with such a choice [109]. Therefore, careful consideration of the multi-modal network properties becomes crucial in ensuring its effectiveness. By optimizing the design and planning of multi-modal transportation options, resources can be better utilized, leading to improved efficiency and sustainability in the overall transport system [88]. However, it is worth noting that the capital costs associated with the implementation of the TEN-T network are deemed substantial. The funding schemes to support these infrastructure investments have posed greater challenges than initially anticipated [103]. As a result, careful consideration of the multi-modality aspect of the network with information integration could be key in addressing the financial aspects to ensure the successful realization of the TEN-T network. Undoubtedly, allowing passengers to have a wider range of destinations accessible to them will result in better network integration and thus, become a stepping stone to shift the mobility behavior in Europe [22].

Moreover, the European Union has taken significant policy measures that align with the expansion of rail infrastructure facilitated by the Trans-European Transportation Network. A notable initiative in this regard is the Fourth Railway Package, introduced by the European Commission in 2016. This legislative package aims to revitalize the rail sector by fostering a more competitive market environment [30]. The Fourth Railway Package introduces measures to enhance competition within the rail industry. One key aspect is the requirement for public service contracts to be awarded through tenders, thus promoting a competitive market for railway operating companies [28]. By adopting this approach, the European Union aims to increase the interoperability of railway infrastructure and eliminate administrative and legislative discrepancies between member countries [29]. The European Union's objective in removing administrative barriers within the rail sector is to create a more customer-responsive and cost-effective market. By streamlining administrative processes and harmonizing regulations, the European Union aims to make rail transportation a more appealing choice for passenger mobility. This effort supports the broader goal of encouraging a modal shift from less sustainable modes of transport, such as road and air, to more environmentally friendly and efficient rail options. By implementing the Fourth Railway Package and working towards the removal of administrative barriers, the European Union demonstrates its commitment to promoting rail as a viable and attractive option for passenger mobility. These policy actions contribute to the overall objective of achieving sustainable transportation by encouraging modal shifts and reducing the reliance on less sustainable modes of transport.

With the completion and communication of the guidelines for the Trans-European Transport Network (TEN-T) policy, the Directorate-General for Mobility and Transport has undertaken a study to assess the potential impacts of this policy. The study aims to analyze the effectiveness of the policy interventions proposed by the European Commission, in conjunction with the TEN-T guidelines, in facilitating a modal shift that aligns with the 2050 objectives outlined in the Sustainable Mobility Plan for the future

[42]. The study focuses on evaluating whether the current policies, which emphasize sustainability, seamless and efficient transport, the resilience of transport networks, and the use of governance tools, are sufficient to achieve the desired outcomes. To accomplish this, the study employs established models developed by the Directorate, namely ASTRA and TRUST, to establish a baseline scenario and project the future quantitative impacts on transport, economic, and environmental indicators as the TEN-T network becomes operational.By utilizing the ASTRA and TRUST models, the study examines the methodology, inputs, and outputs of these models to provide insights into the potential outcomes of the TEN-T policy. This comprehensive analysis enables a deeper understanding of the projected effects on various sectors, facilitating informed decision-making regarding policy implementation. These models serve as valuable tools in assessing the potential impacts of the TEN-T policy and contribute to the overall understanding of the policy's implications for the future of sustainable transportation within the European Union.

The findings emanating from the aforementioned studies paint a disheartening picture in relation to the achievement of sustainability goals as outlined in the European Green Deal. Despite the implementation of the TEN-T policy, which aimed to promote environmentally-friendly modes of transportation, the impact on passenger transport activity within the air-based mobility sector has been remarkably underwhelming. In fact, the results reveal a disconcerting trend of continued growth in air travel, signifying a lack of effectiveness in curbing the associated environmental impacts. The study's most striking revelation pertains to the seemingly unabated escalation in passenger kilometers traveled by air. Projections indicate a substantial surge from the current 236 billion to a staggering 608 billion by the year 2030, representing a devastating 157% increase over a mere span of 10 years. This trajectory of exponential growth in air travel raises concerns about its compatibility with the overarching sustainability objectives of the European Green Deal. It is worth noting, however, that the establishment of a comprehensive rail network appears to exert a moderating influence on the rate of expansion in air passenger traffic. While this effect is discernible, it is regrettably slow in offsetting the otherwise surging trend. Even with the implementation of such rail infrastructure, it is anticipated that a substantial volume of approximately 840 billion passenger kilometers will still be accrued by the year 2050. This projection represents an estimated 38% increase from the year 2030, underscoring the persistent challenges in achieving significant reductions in air travel demand [42].

It is noteworthy that the aforementioned findings underscore the urgency of the matter at hand. The TEN-T policy, accompanied by corresponding interventions, appears to be effective in enhancing the modal share of rail in passenger transportation, with projections indicating a potential increase of nearly 20% by the designated deadline of 2050 [42]. These findings validate the notion that promoting connectivity, interoperability of infrastructure, and access to sustainable alternatives that enable passengers to reach their destinations expeditiously are pivotal in incentivizing a shift in modal choice. Nevertheless, additional measures are imperative to provide passengers with competitive alternatives vis-à-vis air travel. Enhancing the accessibility and speed of rail systems becomes crucial in the pursuit of this objective, although a novel alternative has recently emerged, attracting significant interest from both communities and industries: the groundbreaking technology of Hyperloop, which exhibits promising potential to be disruptive in the transportation sector.

1.3. Hyperloop

The Hyperloop is an innovative mode of transportation that has garnered attention within the transportation industry over the past decade. It has been pursued as a viable alternative to air travel, rail, and traditional forms of transportation due to its affordability, sustainability, and rapid speed. The concept of the Hyperloop draws inspiration from the pneumatic tube systems used in the 19th and 20th centuries for delivering packages and letters. However, the contemporary ideas for the global transportation system have been derived from Elon Musk's publication titled "Hyperloop Alpha" [87]. This revolutionary transportation system combines elements of air transport and high-speed rail, employing a vacuum tube and magnetic levitation. Pods will be able to travel from and to a station in both directions without crossing each other similar to a High-Speed Rail system. Theoretically, the Hyperloop has the potential to achieve speeds of up to 1200 km/h, and it has emerged as a promising mode of transport that significantly reduces travel times between distant origin and destination pairs. Moreover, its design focuses on sustainability, as the very low-pressure interior layout results in reduced energy consumption [99]. The operational system of the Hyperloop relies on maintaining low pressure, around 100 Pa, which effectively minimizes resistive forces such as drag [106]. This groundbreaking design allows the Hyperloop to connect cities at a faster pace than air travel. For instance, Elon Musk's initial design proposal highlights the potential connection between Los Angeles and San Francisco, which coincides with a recent proposal for a high-speed rail line by the authorities. According to the initial Hyperloop designs, the 506 km journey between the two cities could be completed in approximately 35 minutes [87]. This duration underscores the remarkable speed of the Hyperloop, surpassing both the proposed High-Speed Rail, which takes around 158 minutes, and a typical flight, which would require approximately 75 minutes [106].

Even though Hyperloop is a promising alternative in the transportation sector, the technology is still largely in development. The technical feasibility of Hyperloop has been the main focus of the academic studies revolving around this novel technology as the initial design was made open source by Elon Musk [87, 86].At the time of writing this report, there are no operational Hyperloop lines existing anywhere in the world. However, there are several companies, start-ups as well as student teams interested in the early testing stages. Hardt Hyperloop in the Netherlands, HyperloopTT and HyperloopOne in the United States, and Zeleros Hyperloop in Spain are examples of companies working on Hyperloop. Student teams in TU Delft, TU Munich, and KTH among many others are in the testing stages of Hyperloop technology. Similarly, the European Commission and the national authorities are interested in the potential of Hyperloop and have invested resources into research and development. The next section in this chapter will discuss the knowledge gap that exists on Hyperloop studies.

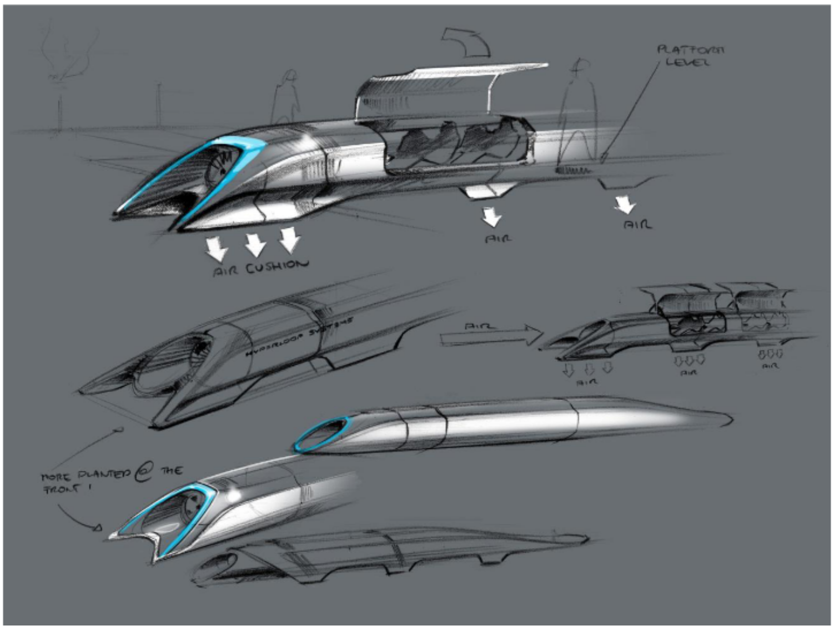

Figure 1.6: Hyperloop design sketch by Elon Musk's SpaceX. Retrieved from: [87]

1.4. Knowledge Gap

The previous sections of this report have laid out the context of the research. There are multi-dimensional considerations in understanding whether the Hyperloop will become a mainstream transport option for passengers. The academia has been searched with the aim of finding literature that studies the impacts of the Hyperloop network designs with single or multiple objectives that fit the disruptive potential of the technology. Due to the novelty of the technology, the amount of studies that focus on Hyperloop is limited. Therefore, studies that discuss electrified rail-based modes such as Maglev or HSR as subjects have also been considered as Hyperloop shares many properties with such modes [116].

The preceding sections of this report have provided the contextual framework for this research endeavor. Understanding the potential for Hyperloop to become a mainstream transportation option for passengers involves multifaceted considerations. Extensive academic research has been conducted to explore the impacts of Hyperloop network designs, either with single or multiple objectives, in line with the disruptive nature of this technology. Given the novelty of Hyperloop, the existing body of literature specifically focused on Hyperloop is limited. Consequently, studies examining electrified rail-based modes such as Maglev or High-Speed Rail (HSR) have also been included in this review, as Hyperloop shares similarities with these modes [116]. These articles often focus on singular objectives, examining the potential effects of infrastructure decisions aligned solely with the same objective, with the intention of minimizing or maximizing specific impacts. The studies included in the literature review can be found in Table 1.1, with their transport mode, the inclusion of network design, and objective criteria considered. Similarly, another overview with the general subjects of the study for each paper can be found in Table 4.1 .

Among the selected articles, only one paper by Premsagar & Kenworthy (2022) [98] considers multiple objectives, specifically exploring the environmental and economic impacts of Hyperloop. Gkoumas & Christou (2020) [51] provide a literature review that summarizes existing research on Hyperloop infrastructure implementation, highlighting key challenges such as high testing and infrastructure costs. Kirschen & Burnell (2022) [66] utilize a model to optimize and minimize the total cost of operation per kilometer, primarily concentrating on operational specifications rather than network design. Jeker (2019) [64] aims to minimize infrastructure construction costs for new Hyperloop links but overlooks other criteria such as operational costs, sustainability, or indirect benefits. Rho & Kim (2022) [102] evaluate two potential network designs for a Hyperspeed Rail System in South Korea, employing capital costs as the sole evaluation metric. Tudor & Paolone (2021) [118] employ a mathematical model to minimize energy usage in the Hyperloop system and propose technical and operational improvements, but they do not address network design considerations in relation to energy usage. Markvica et al. (2018) [77] examine key performance indicators for potential transport technologies, offering valuable insights into the assessment of transport innovations' impact. Premsagar & Kenworthy (2022) [98] explore the direct and indirect impacts of Hyperloop implementation on urban planning, the environment, and the economy, but they fail to examine the relationships between these factors or the trade-offs that may arise. Neef et al. (2020) [89] emphasizes the importance of stakeholder participation and process design in their study on future transport system estimation. Through interviews and workshops with industry experts, they evaluate different scenarios, including one involving a transport transition driven by Hyperloop.

Al Haddad et al. (2022) [1] conducted a survey in Germany to gain insights into user preferences regarding factors influencing passenger mode choice. Their findings indicate that mode-related characteristics such as travel time, travel cost, and safety significantly impact the selection of Hyperloop as a preferred mode of transport. Volters-Dorta et al. (2018) [120] employed a Multi-nominal Logit (MNL) model to predict the short-term effects of a modal shift from air travel to Hyperloop in the event of a Hyperloop route between Los Angeles and San Francisco. Similarly, Borghetti (2023) [10] conducted a stated preference survey combined with an MNL model to determine the probability of user choice among High-Speed Rail (HSR), Hyperloop, and air modes. Their analysis suggests that the lowest viable ticket price in Italy should be set at 80 euros per trip per passenger in order to maximize Hyperloop's user base. In a similar vein, Pagliara et al. (2012) [95] conducted a study exploring the modal shift from air to rail and investigated the significant factors influencing passenger decisions. Agrawal et

Source	Author(s)	Transport Mode	Inclusion of Network Design	Criteria(s) Considered
[118]	*Tudor D. and Paolone M. (2021)*	Hyperloop	No	Energy Demand
[92]	*Oosterhaven J. and Romp W.E.(2002)*	Maglev & HSR	Yes	Indirect Economic Impacts
[51]	*Gkoumas K. and Christou M. (2020)*	Hyperloop	No	-
[64]	*Jeker S. (2019)*	Hyperloop	Yes	Infrastructure Costs
[66]	*Kirschen P. and Burnell E. (2022)*	Hyperloop	No	Infrastructure & Operation Costs
[89]	*Neef R., et al. (2020)*	Hyperloop	Yes	Infrastructure Costs
[102]	*Rho H. and Kim H. (2022)*	Maglev & HSR	Yes	Infrasturcture Costs
[77]	*Markvica K. et al. (2018)*	Hyperloop	Yes	Sustainability
[98]	*Premsagar S. and Kenworthy J. (2022)*	Hyperloop	No	Economic & Environmental
[1]	*Al Haddad C., et al. (2022)*	Hyperloop	No	-
[120]	*Voltes-Dorta A. and Becker E. (2018)*	Hyperloop	No	-
[10]	*Borghetti, F. (2023)*	Hyperloop	No	-
[4]	*Agrawal, P., & Pravinvongvuth, S. (2021)*	Hyperloop	No	-
[95]	*Pagliara, F. et al. (2012)*	HSR	No	-
[18]	*Canca D., et al. (2014)*	HSR	Yes	Infrastructure Costs

Table 1.1: The authors, transport mode analyzed, the inclusion of network design and objective the criteria considered of the studies included in the literature review.

Source	Author(s)	Subject
[118]	*Tudor D. and Paolone M. (2021)*	A mathematical model to generate energy consumption minimizing technical design.
[92]	*Oosterhaven J. and Romp W.E.(2002)*	Models to predict indirect impacts (e.g migration and employment) of rail-based infrastructure.
[51]	*Gkoumas K. and Christou M. (2020)*	Identification of current research direction and challenges that lie ahead about Hyperloop infrastructure implementation.
[64]	*Jeker S. (2019)*	Creation of a model that determines the optimal route between two cities with respect to minimizing building costs.
[66]	*Kirschen P. and Burnell E. (2022)*	Usage of HOPS software to optimize technical specifications of a Hyperloop system with respect to minimizing total cost per kilometer.
[89]	*Neef R., et al. (2020)*	Scenario analysis of future integrated transport systems with infrastructure experts estimating impacts.
[102]	*Rho H. and Kim H. (2022)*	Two different scenarios for a possible Hyperspeed Rail System between two cities in South Korea were compared with capital costs as the main parameter.
[77]	*Markvica K. et al. (2018)*	Sustainability & Identification of key performance indicators for future sustainable transport technology alternatives and their potential impacts.
[98]	*Premsagar S. and Kenworthy J. (2022)*	identification and elaboration on potential urban, transport planning, technical, environmental and economic impacts of Hyperloop technology.
[1]	*Al Haddad C., et al. (2022)*	A user-preference survey to determine the significant factors in the choice of Hyperloop.
[120]	*Voltes-Dorta A. and Becker E. (2018)*	A MNL model to determine the potential shift from air to Hyperloop in California.
[10]	*Borghetti, F. (2023)*	A stated preference survey to find mode choice probability with respect to Hyperloop price.
[4]	*Agrawal, P., & Pravinvongvuth, S. (2021)*	An MNL model with a case study based in Bangkok-Chiang to calculate demand elasticity of Hyperloop.
[95]	*Pagliara, F. et al. (2012)*	Logit MNL model made from stated preference survey to determine factor for HSR choice.
[18]	*Canca D., et al. (2014)*	A mathematical model to integrate network design, line planning and fleet minimization.

Table 1.2: The authors and subjects of the study for studies considered included in the literature review.

al. (2021) [4] utilized a nested logit model to anticipate the modal shift that could occur if a Hyperloop line were established in the Bangkok-Chiang Mai corridor. They calculated the elasticities of Hyperloop demand in relation to travel cost, travel time, and monthly income of users. Their findings suggest that 51% of all passengers would transition to Hyperloop from other transportation modes. Canca et al. (2014) [18] formulated a mathematical model to simultaneously address strategic planning and tactical planning aspects in rail-based infrastructure networks.

The literature review reveals a critical knowledge gap in Hyperloop research. While studies have identified key performance indicators for success and failure factors, there is a lack of comprehensive analyses that explore trade-offs among these factors. Optimization models have been developed to assess technical and operational specifications of Hyperloop designs, yet network design, which significantly influences mobility behavior and mode accessibility, has received limited attention in terms of potential modal shifts between transportation modes. Out of the studies selected only 6 consider the network design but did so with singular objectives considered. Consequently, there is a significant knowledge gap regarding infrastructure design prospects, considering the anticipated path dependency resulting from substantial investment costs. None of the reviewed articles incorporate more than one factor in their optimization models, underscoring the need for a holistic perspective to maximize the benefits of public transport systems [123]. Therefore, a multi-objective network design optimization model is indispensable to capture the systems-of-systems attribute and address the complexity inherent in this problem. Furthermore, even though there are studies that discuss potential modal-shifts take the network design as an input with studying a singular corridor. There is a lack of studies to explore the relationship between the network design objectives, the network design itself, and the resulting modal shift on a European level.

1.5. Research Questions

The observations from the conducted literature review on the subject have revealed the existing scientific gap. The following research question has been identified to address this knowledge gap:

"How does the consideration of varying objective criteria affect the network design of Hyperloop infrastructure?"

The following five sub-questions were generated to further lead this research.

Sub-Question 1: *"What are the current state of Hyperloop technology and the limitations toward Hyperloop realization?"*

Sub-question 1 will aim toward creating an initial understanding of the Hyperloop technology. A literature review will be conducted to have a better overview of the strength and weaknesses of the technology. This analysis will serve as a basis for the subsequent research on Hyperloop network properties.

Sub-Question 2:*: What are the key performance indicators to evaluate an optimal design of a Hyperloop network?"*

This sub-question builds on the output from the first sub-question. The identified strengths and weaknesses will be detailed and substantiated. The rationale for this research task is to identify which purposes can Hyperloop transport networks prioritize.

Sub-Question 3: *"What would be the elements and structure of a suitable Hyperloop network?"*

For sub-question 3, the outputs of the previous three chapters will be utilized as inputs for model conceptualization. The key performance indicators and the selected objectives will be used in the model to create a multi-objective optimization model of a service network design.

Sub-Question 4: *"How can we quantify the modal shift in a global transportation system as a result of Hyperloop realization?"*

This sub-question will utilize the outputs of the multi-objective model created in the previous sub-questions of the study. The generated network designs will be evaluated in terms of the determined objectives of the transport network. A sensitivity analysis will be conducted to further understand the importance of certain design choices and their effects on the key performance indicators.

Sub-Question 5: *"What are the societal consequences of different network design choices in a global transportation system?"*

The last sub-question, will present the trade-off and the relationship between these objectives quantitatively to guide decision-makers by explicitly identifying societal impacts. The different solutions of Hyperloop networks will be evaluated further to examine the resulting network topologies to achieve a realistic and balanced decision-support tool.

1.6. Report Structure

The rest of this report is structured as follows. Chapter 2 aims to answer sub-question 1 and sub-question 2 via a literature review of the current studies on network design and Hyperloop technology itself. Chapter 3 will introduce the methodology used in this study and will be attempting to answer sub-question 3. The methodology will be applied in a quantitative modeling approach in Chapter 4. Subsequently, Chapter 5 will make use of a case study to apply the aforementioned model. The inputs and outputs of the case study will provide an answer to the last two sub-questions. Lastly, Chapter 6 will present the results of the case study and will be followed by a discussion of these results as well as limitations, recommendations for further research, and the conclusion in Chapter 7.

2

Transformative Potential of Hyperloop

Chapter 1 has introduced the context of research and gave a brief introduction to the Hyperloop technology. In this chapter, Hyperloop technology will be detailed further. The potential positive impacts and weaknesses will be discussed to give a better overview of the disruptiveness of the technology as a transportation mode.

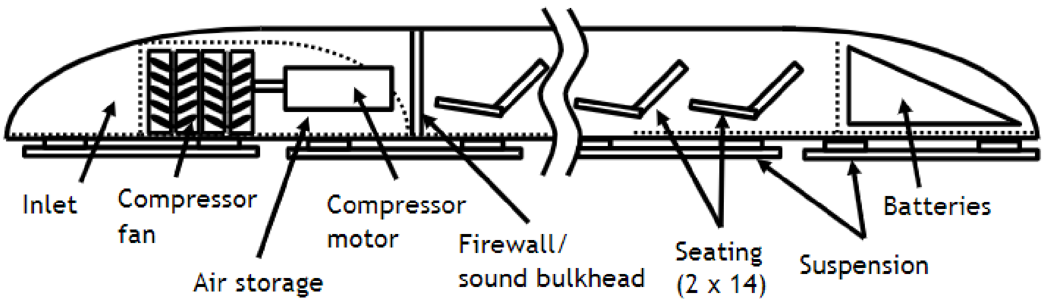

Figure 2.1: Hyperloop design concept by Elon Musk's SpaceX. Retrieved from: [87]

The technical design of Hyperloop systems is firmly rooted in the application of Magnetic Levitation (Maglev) systems. Maglev systems utilize magnetic levitation and propulsion mechanisms to enable the smooth movement of pods or vehicles with minimal physical contact with the underlying infrastructure. By eliminating frictional forces, this arrangement allows for efficient and high-speed travel [106]. Notably, Maglev trains are currently operational primarily in East Asian countries, with Japan's "Shinkansen" Maglev trains reaching impressive speeds of up to 603 km/h [49]. However, one notable technical obstacle that limits the speed of Maglev trains is the aerodynamic drag force acting opposite to the direction of travel. As the velocity of the vehicle increases, the drag forces escalate substantially, necessitating a significant increase in power consumption. In fact, approximately eight times the power is required as the velocity doubles [106]. To overcome this challenge, the Hyperloop design proposed by SpaceX incorporates a Linear Induction Motor (LIM) to counteract the adverse effects of aerodynamic drag. The Linear Induction Motor (LIM) serves the critical function of accelerating and decelerating the vehicle, ensuring the required acceleration levels to achieve the Hyperloop's targeted top speed of around 1200 km/h [87]. Furthermore, SpaceX recognizes the importance of sustainability in the Hyperloop transportation concept. To address this, they have proposed powering the linear induction motor with solar panels. In the initial design, a Hyperloop pod is projected to consume an average of 21 MW of energy. In response, SpaceX plans to integrate solar panels into the system, with an extensive capacity to generate 57 MW of energy. This surplus energy can then be stored in a dedicated battery situated within the pod itself as can be seen on Figure 2.1. The stored energy is subsequently utilized during the energy-intensive processes of acceleration and deceleration, optimizing the overall efficiency of the system [87]. Using the Los Angeles - San Francisco route as an illustrative example, SpaceX posits that the energy consumption of the Hyperloop system would be significantly lower compared to any other mode of transportation between these major cities [87]. The findings are graphically depicted in Figure 2.5.In the operation phase, Hyperloop is deemed to have zero emissions, which is very promising in the sustainability aspect. This observation suggests that Hyperloop has the potential to offer passengers a more sustainable and expeditious alternative, leading to undeniable environmental advantages if there is a consequential shift in the transport mode share pattern. It should also be mentioned that the analysis so far has ignored the emissions that might be emitted through the entire life cycle of the system and thus, the sustainability of Hyperloop is overestimated. However, there is a lack of information and study on this aspect of Hyperloop systems as of now [116].

The Hyperloop operates within a tube structure with a cross-sectional area of 8.55 square meters, featuring an inner diameter of approximately 3.3 meters. To support the entire system, pillars are employed, suspending the tubes above the ground. The decision to use such a configuration stems from a cost perspective, as the construction of tunnels beneath the surface using the boring process was deemed prohibitively expensive [87]. Moreover, underground tunnel construction entails significant time and resource requirements, while also necessitating land acquisition. By utilizing above-ground pillars, the system can potentially leverage existing rights of way, such as highways, simplifying access and circumventing the capital costs associated with land purchases. However, depending on the country of construction, ”air rights” may still need to be acquired [116]. Another vital aspect of a functional Hyperloop system is the presence of well-designed stations. These stations would feature ”arriving” and ”departing” chambers to facilitate the necessary adjustment of atmospheric pressure, allowing passengers to embark and disembark the vehicles [52]. An example design of such a Hyperloop hub can be seen in Figure 2.4.The operations of the Hyperloop system itself are similar to any rail-based system as can be seen in Figure 2.3. Given the nascent nature of the technology and the inherent uncertainties associated with its implementation, it is crucial to acknowledge both the limitations and potential advantages of the Hyperloop that distinguish it from existing modes of transportation [99]. Due to the uncertainties that exist in multiple dimensions of Hyperloop such as the key elements and objectives of a suitable network, the ability to reach the aforementioned potential, and the effects it will have on an entire transportation system, further research on the subject is required. Due to the uncertainty revolving around precise cost estimation and the technology itself, it is difficult to estimate the public perception of Hyperloop.

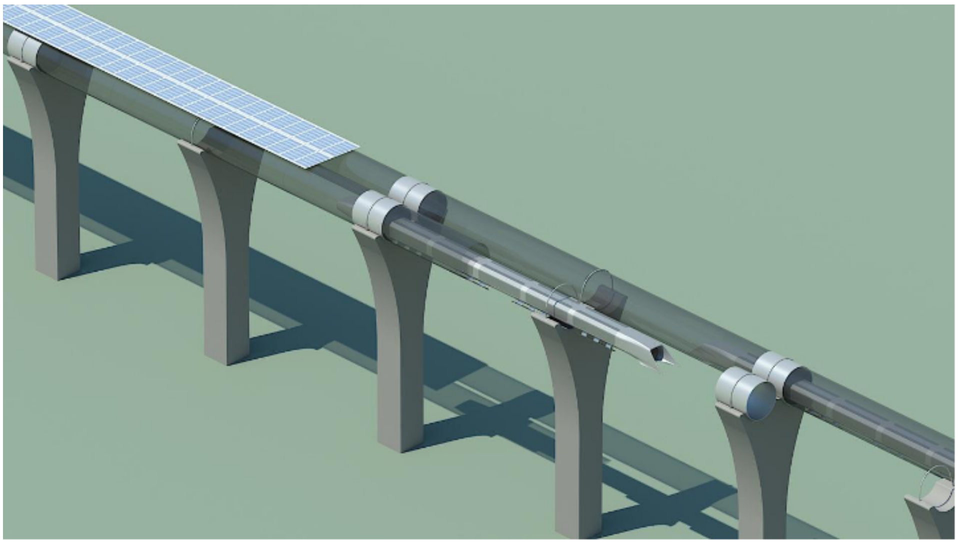

Figure 2.2: Depiction of a Hyperloop tube, a vehicle with attached solar panels on the tube. Retrieved from: [87]

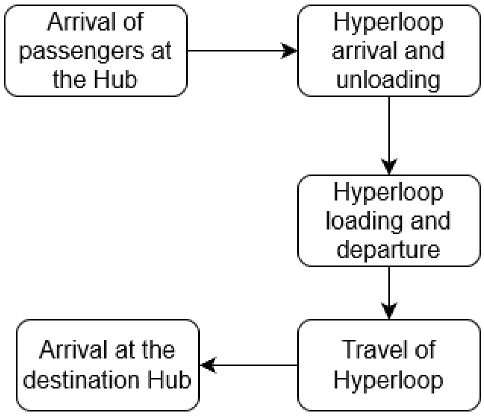

Figure 2.3: A typical sequence of operations in a Hyperloop operation. Retrieved from: [99]

Figure 2.4: Design of a potential Hyperloop Hub. Retrieved from: [87]

2.1. Strengths of Hyperloop

The potential unique strengths of Hyperloop lie in its competitiveness towards better environmental externalities as well as providing the passengers with a viable option to travel to medium-long distances. As explained in the previous section, this property of Hyperloop makes it a good alternative to short-haul flights.

2.1.1. Travel Time

The travel time offered by the Hyperloop system stands out as a significant advantage. It is essential to delineate the different components that contribute to the overall travel time. These components can be categorized into four main aspects: access/egress time, waiting time, in-vehicle time, and interchange time [52]. The access and egress time are influenced by various factors, primarily the location of the hubs and their connectivity to other transportation modes within urban areas. Therefore, spatial planning plays a crucial role in determining access and egress time, as it can impact mode choice behavior and accessibility [56]. Additionally, the access time may be influenced by the security measures implemented at Hyperloop stations. If extensive security checks, akin to airport procedures, are deemed necessary, the access time could be significantly extended. Conversely, if security measures similar to those employed in rail systems are adopted for Hyperloop, the time spent on security screening may be minimal or even nonexistent [116]. In terms of in-vehicle time, the Hyperloop system is poised to offer the shortest travel duration compared to other transportation modes for a given origin-destination pair. This holds true for both the maximum speeds achievable by the pods and the average speed of the vehicle. For instance, a journey from Los Angeles to Las Vegas, covering approximately 434 km, would take just 26 minutes with Hyperloop. In contrast, the same trip would typically require around 70 minutes by air and 84 minutes using the current capabilities of high-speed rail. Thus, this substantial advantage has the potential to be a game-changer, causing disruption in the transportation sector and alleviating congestion in other transportation infrastructures. The remarkable reduction in travel time offered by Hyperloop has the capacity to transform regional connectivity, facilitate economic growth, and enhance the overall efficiency of long-distance travel. By significantly shortening the journey duration, Hyperloop has the potential to reshape travel patterns, encourage modal shifts, and contribute to a more time-efficient and interconnected society. The waiting time and interchange time are also dependent on auxiliary design choices in both the infrastructure and network. The frequency of available trips is critical to determine the waiting times. However, the alignment of supply and demand is critical to not waste resources or avoid higher waiting times at the stations [116]. Similarly, the interchange times are highly dependent on the network design [59]. If a direct link between a desired origin-destination pair does not exist, the passenger might still choose Hyperloop if attractive interchanges are available rather than opting for another transport mode.

2.1.2. Energy Consumption

Hyperloop systems are meticulously designed to exhibit a high degree of energy efficiency. The incorporation of advanced propulsion and magnetic levitation systems enables Hyperloop to achieve remarkable speeds while consuming minimal energy per passenger per kilometer (refer to Figure 2.5). SpaceX asserts that the Hyperloop tubes themselves can be equipped with solar panels, facilitating the generation of renewable energy to power the entire system. Consequently, the expectation is that Hyperloop operations will rely entirely on clean and sustainable energy sources [116]. Preliminary research suggests that a Hyperloop system could exhibit energy efficiency levels up to five times greater than air-based modes of transportation and twice as efficient as rail-based modes. Furthermore, the above-ground infrastructure configuration of Hyperloop systems offers the potential to mitigate negative externalities associated with land use, thereby minimizing ecological impact. Consequently, the deployment of the Hyperloop could contribute significantly to the reduction of carbon emissions stemming from transportation activities, provided that passengers find the option sufficiently appealing. However, it is crucial to consider the indirect emissions associated with the construction of Hyperloop infrastructure. To comprehensively evaluate the overall effects of Hyperloop systems and compare them against the sustainable transport objectives of Europe, further studies should incorporate and address these indirect emissions. By accounting for the complete life cycle of the system, a more comprehensive assessment can be conducted to ascertain the full environmental impact of Hyperloop and its alignment with sustainability goals.

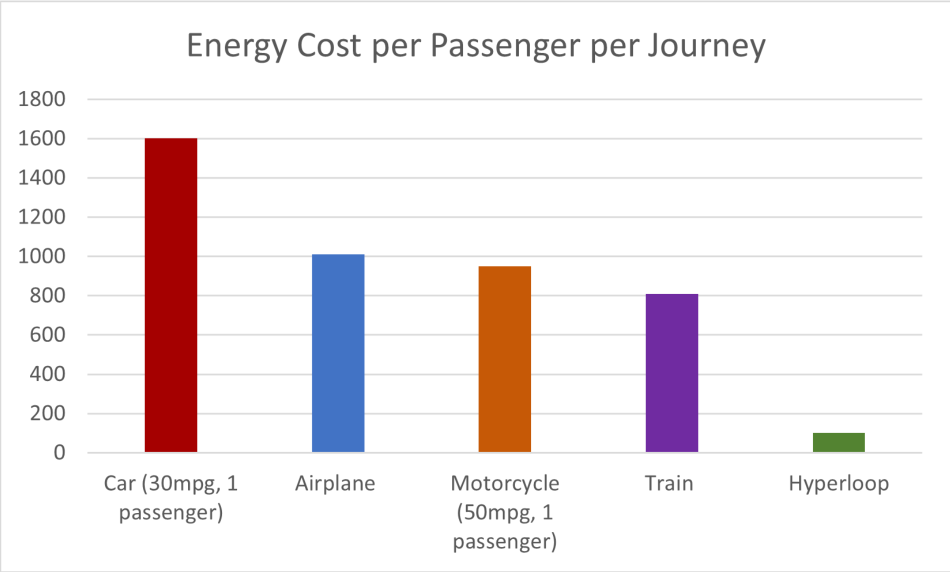

Figure 2.5: Energy cost per passenger per journey between Los Angeles and San Francisco of 506 km. Own elaboration. Data Retrieved from: [87, 34]

2.2. Weaknesses of Hyperloop

It is important to note that these weaknesses are being actively addressed through ongoing research and testing around the world. One may expect these factors to change as the technology continues to evolve.

2.2.1. High Capital Costs

The infrastructure required for a Hyperloop system to run can be defined as a High-Performance Transport Infrastructure [77]. This means that the infrastructure needs to be able to handle high throughput as well as be technologically adequate to support the almost sonic speeds. Furthermore, the initial suggestion for Hyperloop is to be built upon pillars that can suspend the vehicle in the air [87]. The capital cost could therefore be divided into two main categories, the tubes constitute the first category which includes the magnetic levitation systems, solar panels on the tubes, and the pillars that support the tubes themselves. The second category refers to the stations which may include the docking and undocking stations for the prospective passengers. The white paper Hyperloop Alpha has outlined that stations would cost around 125 million US Dollars. They also estimate that the construction of a tube that has a diameter of 3 meters will cost 650 million US Dollars for a route of roughly 1100 kilometers. Combined with the costs of pillars, propulsion systems, and solar panels the total cost of construction will be around 5.4 billion US Dollars between Los Angeles and San Francisco compared to 70 billion US dollars for the High-Speed Rail line on the same route, further intensifying the cost advantage Hyperloop could have. [38]. Translated per mile, this becomes 10 million US Dollars per kilometer for Hyperloop. [87]. However, this estimation has received many criticisms of underestimation [116]. For example, in another proposed Hyperloop line between Abu Dhabi and Dubai, the estimation was 52 million US Dollars per kilometer [57]. Furthermore, it is imperative to mention that the capital costs will change substantially depending on the geography of the proposed line. Tunnels might be required on certain parts of the route to follow existing rights of way such as highways or railroads. These constraints would increase the costs even further [94]. Hence, careful cost estimation studies should be conducted for each specific route proposal to get an insight into complete costs.

Mega-projects such as international high-speed rail lines are shown to have large construction costs and 9 out of 10 projects saw actual costs being higher than anticipated. For rail the average cost escalation is 45%. [44]. It is likely that a mega-project like Hyperloop which shares similarities to rail-based modes would also be subject to cost escalation. This could negatively affect the political feasibility of the project as other projects become more attractive [41]. The huge costs mean that private companies might require extensive subsidies from the public sector to be able to make Hyperloop functional. This is especially true considering the low capacity of the Hyperloop of around 28 passengers per pod prevents taking advantage of economies of scale for Hyperloop [52]. Although, many of the cost considerations are highly sensitive to the design choices made in the earlier stages of development and could be adjusted to lower the capital costs [35].

The infrastructure necessary for the operation of a Hyperloop system can be defined as a High-Performance Transport Infrastructure [77]. This implies that the infrastructure must have the capacity to handle high throughput and be technologically advanced to support the high speeds achieved by the system. Additionally, the initial proposal for the Hyperloop suggests constructing it on pillars that can suspend the vehicles in the air [87]. Consequently, the capital cost can be categorized into two main groups. The first category encompasses the tubes, including the magnetic levitation systems, solar panels on the tubes, and the supporting pillars. The second category pertains to the stations, which may include the docking and undocking stations for passengers. According to the white paper Hyperloop Alpha, the estimated cost for stations is approximately 125 million US Dollars. Furthermore, they project that constructing a tube with a 3-meter diameter for a route of around 1100 kilometers would cost approximately 650 million US Dollars. When combined with the costs of pillars, propulsion systems, and solar panels, the total construction cost is estimated to be around 5.4 billion US Dollars for the Los Angeles to San Francisco route, in contrast to the 70 billion US Dollars for the High-Speed Rail line on the same route, thus highlighting the cost advantage that the Hyperloop could potentially offer [38]. This translates to approximately 10 million US Dollars per kilometer for the Hyperloop (Hyperloop Alpha, citation needed). However, this estimation has received criticism for underestimating the costs [116]. For instance, another proposed Hyperloop line between Abu Dhabi and Dubai was estimated to cost 52 million US Dollars per kilometer [57]. It is important to note that the capital costs will vary significantly depending on the geographical characteristics of the proposed route, as tunnels may be required to follow existing rights of way such as highways or railroads, further increasing the costs [94]. Therefore, thorough cost estimation studies should be conducted for each specific route proposal to obtain a comprehensive understanding of the total costs.

Furthermore, it is worth considering that mega-projects like international high-speed rail lines have historically experienced substantial construction cost escalations, with actual costs exceeding initial estimates in 9 out of 10 projects, and an average cost escalation of 45% for rail projects [44]. It is reasonable to assume that a mega-project like the Hyperloop, which shares similarities with rail-based modes, would also be susceptible to cost escalation. This potential escalation could adversely affect the political feasibility of the project, as other projects may become more appealing [41]. Given the significant costs involved, private companies may require substantial subsidies from the public sector to make the Hyperloop economically viable. This is particularly relevant considering the relatively low capacity of the Hyperloop, with each pod accommodating approximately 28 passengers, which limits the potential economies of scale [52]. However, many cost considerations are highly sensitive to design choices made in the early stages of development and could be adjusted to reduce capital costs [35].

2.2.2. Safety

Elon Musk's initial design has encountered criticism regarding safety and comfort aspects. The advantages of the system based on its performance, such as the remarkable speeds achieved by Hyperloop, may contribute to significant risks. In the event of a technical malfunction leading to pod failure, the close proximity of the pods, combined with the immense kinetic energy generated at high speeds, would result in a catastrophic collision [98]. The construction of a protective tube surrounding the Hyperloop aims to shield the vehicles from severe weather conditions [82]. However, due to the enclosed nature of the system, it necessitates the implementation of comprehensive emergency systems to facilitate prompt evacuation, similar to those found in urban-rail systems such as subways [110]. This is particularly crucial given the inherent difficulty in eliciting the desired response from passengers during emergency situations [45]. Furthermore, as Hyperloop operates within a near-vacuum environment, maintaining cabin pressure becomes essential, akin to protocols observed in airplanes, necessitating the presence of oxygen masks within the pods [63].

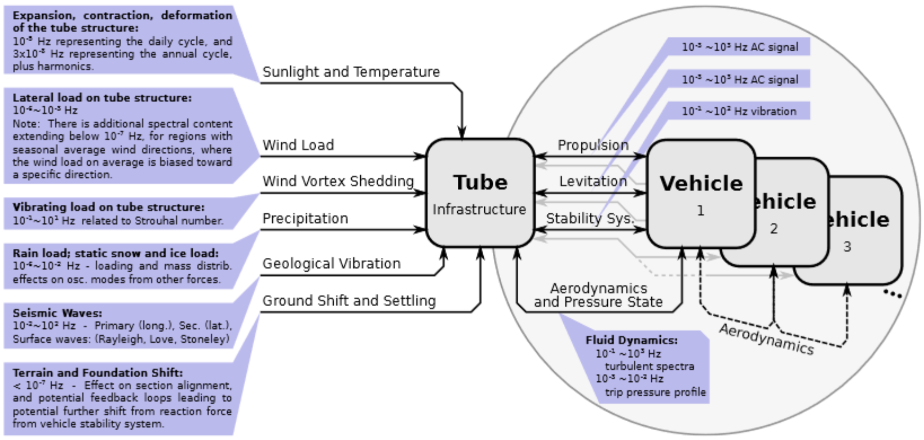

Figure 2.6: A diagram of all forces in action at a Hyperloop system. Data Retrieved from: [63]

The design of acceleration and deceleration mechanisms employed within the Hyperloop hubs is of particular concern due to the approximately 1g force exerted on passengers, which can have detrimental effects on the human body [9]. The initial proposals indicate the presence of emergency personnel at Hyperloop stations, with the stipulation that completion of the route must take precedence before any intervention can occur [87]. Moreover, if the infrastructure is constructed using pillars, as suggested in the initial designs, it must exhibit resilience against seismic activity. A comprehensive analysis of the forces experienced within the system is presented in Figure 2.6. Notably, strategies for resistance have facilitated the establishment of similar high-speed rail infrastructures in countries such as Japan, which are known for their frequent and powerful earthquakes [106]. Therefore, adopting preventive design choices akin to those employed in high-speed rail systems could be implemented in the development of Hyperloop infrastructure. While safety has been a focal point in studies pertaining to the Hyperloop and its associated infrastructure, the uncertainty surrounding design decisions and the lack of extensive real-world testing raise concerns among the general public regarding the perception of Hyperloop [86].

To summarize, the strengths and weaknesses of a potential Hyperloop system are important design aspects that are to be considered. The realization and the success of the innovation would depend on these factors amongst many more [41]. Throughout the rest of this report, these aspects will be considered the main critical design aspects that will also act as objective criteria for a Hyperloop network design.

3
Methodology

This chapter will provide a background of the methodology used in this study. In the sections that follow, a general literature review will be given on Network Design Problems and Multi-Objective Optimization models.

3.1. Infrastructure (Network) Design

Network design problems have existed ever since the inception of infrastructures themselves. Commonly networked infrastructures are expensive to build and after initial construction path dependency causes changes very unlikely [58]. Hence, the initial decisions have critical consequences and must be taken optimally. There are several different methods to identify the optimal way to create a network of nodes and links. These design problems can be solved with methods such as mixed-integer linear or non-linear programming (MILP or MINLP), graph theory, and/or agent-based models [58]. There are different approaches to the solution methodologies such as using meta-heuristics like the Kruskal's algorithm [69] in the case of graph theory and using commercial solver software (such as CPLEX) to solve operations research problems to optimality in the case of MILP models.

Operations research serves as an effective basis to analyze the efficiency and performance of physical infrastructure. In order to reap the benefits of public transport, optimization models have been utilized by decision-makers to make informed analytical decisions [104]. Furthermore, the network design of public transport is critical for the successful implementation and realization of objectives [90]. Any public transport network could be viewed as a set of nodes connected by edges [75]. Rail-based modes such as Hyperloop and High-Speed Rail require specialized infrastructure to be operational, therefore the network design should reflect the specific structural characteristics and technical requirements of the mode [100]. In order to decide upon a suitable network, planners often use a hierarchical approach to the problem. Figure 3.1 illustrates the different phases and the sub-problems to be solved iteratively. The outputs of the problems in the earlier hierarchy are used as inputs on the subsequent problems as trying to solve all of the problems simultaneously complicates the problem making way for computational difficulties. [16].

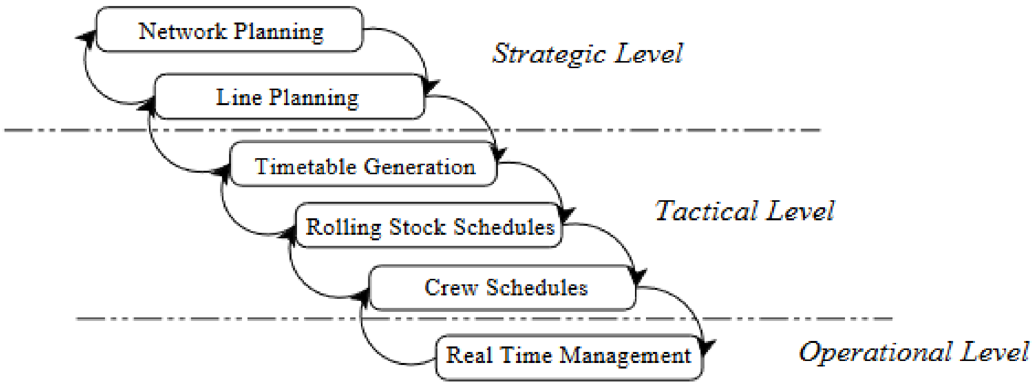

Figure 3.1: Phases of Railway Planning. Retrieved from: [75]

The strategic level of railway planning is highlighted by the decision to construct the infrastructure. Mainly, decisions are optimally deciding the location of the hubs and connecting the said hubs with the necessary infrastructure [75]. Furthermore, these decisions have to include the demand generated by possible passengers who want to travel to a specific location. This is also often referred to as the Origin-Destination demand between two potential nodes of the network. The demand information is important to align the supply of the infrastructure to the demand of the passenger as these decisions often have political and economic backgrounds [16]. These problems are often called facility-location problems or hub-location problems in the literature. One of the first studies on the subject of hub-location problems has been generated by Hakimi (1964) [70] and O'Kelly (1987) [91]. O'Kelly has generated a quadratic integer programming model to determine the locations of hubs within a network via several heuristics. The usage of heuristics means that the solutions generated could also be sub-optimal. Skorin-Kapov et al. (1996) [112] has improved the model formulated by O'Kelly (1987), by introducing a tabu-search solution approach. Ernest and Krishnamoorty (1996) [39] build upon the formulation by using a simulated annealing approach to the solution methodology to improve the computational time. There are also examples in the literature that combine network planning with line planning such as the mathematical formulation of Melkote and Daskin (2001) [84] or the studies conducted by Laporte et. al. (1997) [71] who classify such problems as an adjusted traveling-salesman problem.

The facility location problems require a set of potential locations that are to be considered in the model. Furthermore, the network topology selected for any given infrastructure has profound consequences for the performance of the network [96]. The desired network could have several different characteristics. Firstly, the demand and supply nodes must be distinguished from one another or alternatively, all nodes could be both sources and sinks simultaneously [58]. Such problems are often classified as multi-source-multi-sink network problems, where all nodes act like transshipment points where single or more commodities are transported through [85]. Several studies using the multi-source-multi-sink problem exist in the literature. For instance, Hu (2006) [61] implements such a model on optimal hub location decisions for a communication infrastructure network. Furthermore, in such problems the routes between the selected facilities have specific costs associated with them such as capacity, time, or monetary costs [101]. Facility Location problems are often combined with the network design even further on the strategic level of planning by including three specific decisions to be made: 1) the decision to select a location for a hub, 2) the decision to connect the selected hubs and 3) allocation of resources or demand points to the selected hubs to be transported. There are instances in the literature where more decisions are integrated into the facility location-network design problems. For example, Aghezzaf (2017) [3] and Amiri (2006) [6] include the decision of capacity planning alongside the facility location problem. The decision of selecting a transport mode has been included in the problem by Wilhelm et. al. (2005) [125] and Chakravarty (2005) [19]. A more comprehensive literature review for the facility location problem with more characteristics, solution methods, and sectors compared can be found in Melo et. al. (2008) [85]. The demand data can also be considered deterministic or stochastic in these types of problems. Models can be adjusted to consider the possibility of changes in demand in both the long and short-term decisions that might follow. [37]. Figure 3.2 showcases an overview of time horizons and planning stages.

The decision of constructing transport infrastructures is a sub-set of facility-location and network design problems. Therefore, the facility-location network design problem will be the basis of the model built for the purposes of this study. The problem will be considering all possible locations to construct Hyperloop hubs as multi-source and multi-sink nodes where all potential Hyperloop hubs will be demand and supply points simultaneously. The following chapters will introduce Multi-Objective Optimization Models and Multi-Nominal Logit Models which will both be important tools used in this study to model a Hyperloop network.

Planning levels

Planning stages	Time horizon	Objective
Strategic level	5–15 years	Resource acquisition
Tactical level	1–5 years	Resource allocation
Operational level	24 h–1 year	Daily planning

Figure 3.2: Planning levels of infrastructure. Retrieved from: [48]

3.2. Multi-Objective Optimization Models

Previously, Chapter 1 has outlined the complexity of transport infrastructure decisions. The infrastructure planning process for public transport decisions is divided into several hierarchical steps as detailed at the start Chapter 3. Even though cost minimization is a straightforward objective for the feasibility of such planning processes, there may be other objectives to consider by policymakers. Examples of these examples could be to maximize reliability, minimize risks, or in the case of the European Green Deal emission minimization [31]. The existence or consideration of different objectives becomes even more challenging when these objectives are conflicting. The trade-offs between the different objectives prevent reaching an overarching solution that achieves every objective simultaneously [67]. The problems where multiple objectives are considered are referred to as Multi-Objective Optimization Models [78]. In these problems, the solutions of the models provide the users with insight into selecting the most attractive amongst the feasible solutions [79].

Achieving a single optimal solution is therefore impossible with conflicting objectives. Instead, every feasible alternative solution is evaluated to determine which solutions yield better objective values than other feasible solutions. If a solution is inferior to another in all aspects, it is referred to as being dominated by another solution. Usually, two generic approaches are taken. First, if it is possible the terms of the different objectives could be combined into a singular objective with weighing methods. However, the analytical decision of the weights given to each term is difficult and could not represent a real-life situation. The second approach is to generate a set of solutions that are Pareto optimal. Pareto Frontier and Pareto optimality are both concepts that have originated from the theory of economics [83]. The set of Pareto optimal solutions is a set of solutions that are non-dominated. Similarly, the Pareto Frontier refers to the set of Pareto optimal solutions where there exists a trade-off between each objective. Hence, it is not possible to improve the value of a given objective without sacrificing another objective value [78].

This study will focus on the creation of a multi-objective optimization model as it is highly suitable for the evaluation of transport infrastructure decisions. The ability to have an outlook on all feasible solutions and the trade-off associated with the different objective values is fitting to the complexity of Hyperloop network design decisions. The objective value will be based on the context of the problem described in Chapter 1 and the technical and socio-economic characteristics of Hyperloop discussed previously in Chapter 2. A detailed description of the model formulated will be given in the upcoming sections of this Chapter. Furthermore, for the purposes of the next chapters of this study, the aim will be to create a Pareto Frontier of Hyperloop network designs with various objective criteria optimized. Specifically, the ϵ-constraint method will be utilized to generate a set of Pareto optimal solutions in the model. The very next section discusses the ϵ-constraint method in more detail.

3.3. The ϵ-constraint Method

The ϵ-constraint method is a commonly used method in the solution methodologies of Multi-Objective Optimization models. In this method, the model is optimized using a single objective and the remaining objectives are used as constraints in the model. If the objective function is minimizing a term, the constraints of other objectives act as upper-bound. Alternatively, if the model is maximizing an objective, the remaining objective terms are used as lower-bound constraints [79]. The formal definition of the ϵ-constraint method can be found in Equation 3.1 below [20]. Assuming we have a sample multi-objective optimization model formulated as:

$$\begin{aligned} \text{max} \quad & f_1(x), f_2(x), ...f_p(x) \\ \text{s.t.} \quad & \\ & x \in S, \end{aligned} \tag{3.1}$$

where x represents the decision variables of the model, $f_p(x)$ represents the objective function and S represents the set of all feasible solutions. Using the ϵ-constraint method, the same problem would be converted in the model given in the Equation 3.2 below.

$$\begin{aligned} \text{max} \quad & f_1(x) \\ \text{s.t.} \quad & \\ & f_2(x) \le e_2, \\ & f_3(x) \le e_3, \\ & ... \\ & f_p(x) \le e_p, \\ & x \in S, \end{aligned} \tag{3.2}$$

where e_p represents a Pareto optimal solution obtained for the objective function with the objective function of $f_p(x)$.

There are several strengths of the ϵ-constraint method, over other generation methods in multi-objective optimization problems. For instance, using the ϵ-constraint method, one can remove redundancy by pruning the solutions that are dominated. This contrast enables the model to have fewer computational problems as multi-objective optimization models could be NP-hard [78]. Furthermore, the ϵ-constraint method alters the set of feasible regions which enables us to have a better overview of the Pareto frontier for a given problem [79]. Due to the ϵ-constraint method removing redundancy, and enabling the output of the model to be analyzed more efficiently by determining the most-efficient set of solutions, the model built for this study will be utilizing this method. This critical advantage will enable to model to showcase potential Hyperloop infrastructure investment choices and their consequences.

3.4. Multi-Nominal Logit (MNL) Models

The Multi-Nominal Logit Model represents a form of discrete choice model that aims to predict user preferences and their selections among a given set of options [81]. In this type of model, the decision-makers are assumed to choose from a range of alternatives based on their perception of the attributes associated with each option. The decision-making process is influenced by the concept of "Utility," which reflects the satisfaction or benefit that users anticipate from choosing a particular alternative. The Utility of an alternative comprises a combination of the relevant attributes and the individual-specific taste, resulting in a utility function that is employed within the framework of discrete choice models known as Random Utility Models (RUM) [7]. The Multi-Nominal Logit Model operates on the assumption that each decision-maker strives to maximize their utility. The utility experienced by a decision-maker can be divided into two components: firstly, the observed utility, which encompasses measurable attributes associated with an alternative, and secondly, the unobserved utility, which takes into account personal taste and lifestyle choices and is subject to random distribution. This latter component is commonly referred to as the error term [81]. The formalization of the Random Utility Model can be found in Equation 3.3.

$$U_{ni} = \beta \cdot V_{ni} + e_{ni} \tag{3.3}$$

where subscript n refers to the decision-making individual, subscript i refers to the alternative, V_{ni} is a vector of the observed attributes associated with the alternative i, β is a term to explain preference parameter for the choice and e_{ni} is the error term. Furthermore, using the Multi-Nominal Logit model it is possible to calculate the probabilities of a decision-maker to select a specific alternative with the following formula [80]:

$$P_{(i)} = \frac{e^{(v_i)}}{\sum_j e^{(v_j)}} \tag{3.4}$$

where $P_{(i)}$ represents the probability that a decision-maker will select the alternative i amongst the set of all alternatives denoted by the summation over all alternatives denoted by j.

The Multi-Nominal Logit (MNL) model is frequently employed in transportation research, particularly when investigating choice behavior among various transport modes. Its primary objective often involves determining the modal split, which refers to the distribution of passengers across different modes of transportation, and identifying the factors influencing their mode selection. Additionally, MNL models find application in estimating passenger route choices, offering valuable insights into GPS services and their capabilities [14]. Policymakers rely on such models to gain essential insights into the determinants of public mode choice, enabling them to design transportation systems that align with public preferences [65]. Therefore, both the MNL model and Random Utility Model (RUM) serve as suitable tools for modal split studies, with a prevalent presence in the existing literature. In this study, a similar methodology will be adopted, employing the MNL approach to conduct a demand analysis specific to the Hyperloop. Moreover, the investigation will explore the factors influencing passengers' decisions to switch from other modes of transportation to the Hyperloop. Chapter 4 will provide a detailed exposition of the model's inputs, formulation, and output. It should also be noted that the usage of Multi-nominal logit models is criticized because of the underlying assumption of independence of irrelevant alternatives. Due to this, MNL models assume that the addition of another option does not change the perception towards selecting between already existing alternatives in the choice model [47]. This assumption does not fully represent the reality of choices made by passengers and some studies use a nested-logit model instead. However, since the focus of this study is on methodological integration, an MNL model has been chosen.

This chapter has explicated and deliberated upon the methodologies to be employed in the present study. Specifically, it has addressed the significance of Network Design problems in transportation infrastructure decision-making. The various categories of facility location problems have been introduced, accompanied by a comprehensive literature review that enhances the reader's comprehension of the associated objectives. Furthermore, the intricacies inherent in public transport infrastructure decisions have been examined, emphasizing the indispensable role of multi-objective optimization models in comprehensively assessing the available alternatives. To address the research objectives concerning the Hyperloop, a suitable solution methodology for a multi-objective optimization model has been outlined, in conjunction with the methodology for conducting a demand analysis specific to the Hyperloop. Chapter 4 will provide an intricate account of the model's properties, underlying assumptions, defined objectives, and associated constraints, culminating in the potential outcomes of the study.

4
Facility-Location Network Design Problem for Hyperloop

Chapter 1 has introduced the context of the problem and identified it. The critical issues in the current transport systems were identified. Using future projections, it has been anticipated that the current policies and the mobility behavior of the passengers will not be enough to curb the emissions to the desired levels. Chapter 2 outlined the potential of the Hyperloop as an alternative investment opportunity to lead a modal shift. Chapter 3 identified key methodology in the literature for key transport infrastructure decisions, modal split, and demand analysis. This chapter will combine the methodology and design steps in formulating a facility-location network design problem for Hyperloop. First in Section 4.1, the general modelling approach will be introduced.

4.1. Modelling Approach

The modeling approach will constitute the strategic planning phase to a prospective Hyperloop infrastructure planning phase. The strategic planning phase can be evaluated in two categories. First, the demand analysis needs to be performed. Second, the identified demand will be utilized in the line planning phase. The entire planning phase diagram which gives a more comprehensive overview can be found in Figure 4.1.

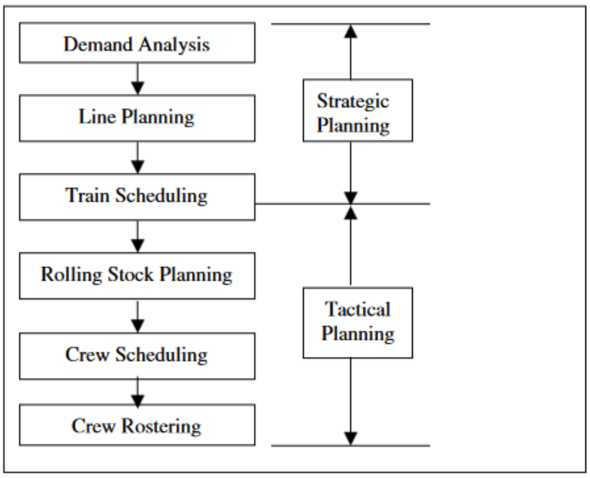

Figure 4.1: Planning levels of infrastructure. Retrieved from: [48]

Demand analysis will be conducted by using a choice model. Specifically, a Multi-Nominal Logit model will be constructed to predict the modal split. Multi-nominal Logit models are often used for the analysis of modal shares and expected usage of a transport mode within transport planning. A more general discussion and explanation of how the MNL model will be used and the outputs can be found in subsection 4.1.1.

Subsequent to the demand analysis for Hyperloop, line planning will take place. In the line planning phase, critical infrastructure decisions will be made such as the placement of Hyperloop stations, and how these hubs will be connected with one another or whether they will be connected at all. Undoubtedly, the structure, topology, and number of opened hubs and connections will have direct consequences on the performance of the Hyperloop system. The key performance indicators of a Hyperloop system will be highly sensitive to the decisions made in this planning phase. A more detailed explanation will be given in Subsection 4.1.2. The flow of the modelling approach can be found in Figure 5.1. The order of operations and the methodology to be utilized are included in the flow.

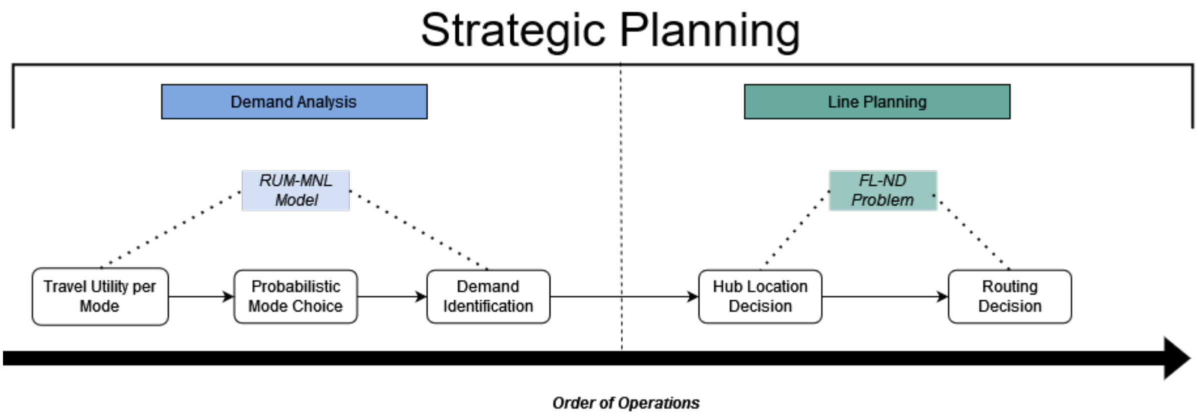

Figure 4.2: Modelling Flow undertaken in this study.

4.1.1. Demand Analysis

Demand Analysis is a critical step to understanding how the public perceives the public transportation system. Therefore, transport planning authorities and/or decision-makers strive to estimate the demand as realistically as possible [117]. This is especially true for the strategic planning phase of realization of any public transport system as explained previously in the study. Technological advancements and the usage of real-time geographical positioning system (GPS) data have been critical in providing a foundation for a more efficient decision-making process. In order to correctly understand the nature of the public transport demand in the public as well as the factors that contribute to the preference, there is a necessity to have data on previous choices made by passengers [122].

Competitive Transport Modes

The demand for transportation is inherently influenced by the availability of alternative modes of transportation and their viability as substitutes for passengers. Therefore, in order to accurately assess the demand for Hyperloop systems, it is crucial to identify the demand for the existing transportation modes that Hyperloop aims to replace. Initially, the concept of a Hyperloop system emerged as a substitute for a planned High-Speed Rail line in California, United States. Elon Musk and SpaceX, in their publication "Hyperloop Alpha," explicitly positioned it as a competitor to High-Speed rail systems worldwide [87]. Consequently, the first transport mode selected for the demand analysis in this study is the High-Speed Rail.

Furthermore, the Hyperloop offers a sustainable, environmentally friendly, and faster alternative for medium and long-distance travel. Its technological advantages make it a viable substitute for short-haul flights, which are widely recognized as environmentally problematic and major contributors to greenhouse gas emissions [25]. Consequently, transportation authorities and decision-makers are actively seeking to replace this mode of transportation with a more sustainable option. Chapter 2 of this study examines the transformative potential of the Hyperloop, particularly in facilitating a modal shift away from air travel. Therefore, short-haul flights have been identified as the second transportation mode of interest for this study.

Origin-Demand Matrices

In the context of demand analysis for strategic decision-making, the construction of origin-destination (OD) demand matrices is a prevalent practice. Origin-Destination matrices encompass data regarding passenger preferences for specific routes, including their point of departure (origin) and intended point of arrival (destination). Such data provides valuable insights into frequently traveled routes with high demand, enabling decision-makers to prioritize and address this demand effectively [117]. However, it is important to note that accessing origin-destination matrices can be costly, as it often requires recording a substantial number of travel diaries. Additionally, capturing supplementary information such as the purpose of the trip or the time of day when the trip was made can contribute to a more comprehensive understanding of mobility behavior [5]. Despite the resource-intensive nature of collecting such data, national and international organizations have made investments in acquiring Origin-Destination demand data.

The objective of this study is to utilize origin-destination demand information related to transportation modes that serve as competitors to the Hyperloop within the transportation sector. Specifically, data pertaining to the usage of short-haul flights and High-Speed rail will be employed to gain insights into the demand patterns between origin-destination pairs. Statistical reports published by airport and rail operating companies, national statistical institutes, and the European Commission's statistical data will be utilized to achieve this objective.

Multi-Nominal Logit Model for Transport Mode Choice

Chapter 3 has introduced the multi-nominal logit models as a viable method amongst discrete choice models to determine the user's choice of transport mode. The concept of "Utility" takes center stage in multi-nominal logit models. The utility is the total benefit passenger will receive upon selecting a specific transport mode for their desired route between an origin and destination pair [80]. The utility is made out of two separate parts, the observable attributes and the unobserved attributes (error term). The underlying assumption in MNL models is that the passengers are offered several alternatives and they make the choice to maximize the utility. In this study, the alternatives available to the traveler will be Hyperloop, High-Speed Rail, and Air.

Multi-Nominal Logit models are highly dependent on how the utility function is defined. The outcome of the mode choice will depend on which attributes of the transportation mode are included in the utility function as well as how much importance travelers place on each attribute. Mode choice models often utilize stated one of the methods to obtain the important attributes according to the travelers. These two methods are stated preference surveys (SP) or revealed preference methods (RP). Revealed preferences information is the explicit choice made and carried out by the traveler regarding the mode choice. For modeling purposes, revealed preferences have several shortcomings. First, the choices made by travelers might make it almost impossible to understand the trade-offs between different attributes. Second, one or a few attributes might dominate the entire choice making it difficult to grasp the importance of all factors involved [36]. These limitations have led the researchers towards using the Stated Preference (SP) method. In Stated Preference methods, the travelers are asked a number of hypothetical questions or given a hypothetical number of alternatives to select from. The responses are thoroughly analyzed statistically to compare the importance travelers give to the different attributes [36].

In the academic literature, numerous instances can be found where Stated Preference (SP) surveys have been employed to comprehend modal split in different regions or behavioral patterns pertaining to a specific mode of transportation. For instance, Ma et al. (2020) [76] conducted an analysis concerning bicycle usage in Delft, the Netherlands. Another noteworthy example is the work of Lin et al. (2023) [73], who employed a Stated Preference (SP) survey to gain insights into the impact of the COVID-19

Transport Mode	Parameter	Name	Units
HSR	c_{HSR}	*Travel Cost*	€ per km
	t_{HSR}	*Travel Time*	minutes
	$Safety_{HSR}$	*Safety Level*	-
Air	c_{air}	*Travel Cost*	€ per km
	t_{air}	*Travel Time*	minutes
	$Safety_{air}$	*Safety Level*	-
Hyperloop	c_{hyp}	*Travel Cost*	€ per km
	t_{hyp}	*Travel Time*	minutes
	t_{hyp}	*Safety Level*	-

Table 4.1: The authors and subjects of the study for studies considered included in the literature review.

pandemic on mode choice in South Korea. Moreover, Hyperloop technology has received considerable attention in scholarly works, leading to the conduct of various Stated Preference (SP) surveys aimed at investigating the public perception of this novel transportation system. Abouelela et al. (2022) [2] undertook a study to determine traveler preferences regarding Hyperloop in Germany. They concluded that the primary factors influencing travelers were travel cost, travel time, and safety level. The study also sought to establish the value of time ascribed by respondents to each hour spent in the Hyperloop system. Similarly, Borghetti (2023) [10] conducted a comparable study in Italy, utilizing ticket prices, Hyperloop trip frequency, travel time, and access time as attributes deemed significant by passengers when making mode choices between Air, High-Speed Rail, and Hyperloop alternatives. Furthermore, Agrawal et al. (2021) [4] identified travel time, travel cost, and frequency as critical attributes influencing mode choice decisions in relation to the Bangkok - Chiang Mai corridor in Thailand. This present study intends to build upon previous research in this field, employing an identical set of mode-specific attributes as a foundation for the utility function. Specifically, travel time, travel cost, and safety level will be the attributes incorporated into the utility function. It is important to note that other factors such as the frequency and sustainability concerns could be included in the utility function to better represent the choice behavior of the passengers. However, due to a lack of studies considering these factors and their importance in the utility of Hyperloop travel, these factors will not be included to avoid misrepresentation.

The utility of a trip will be calculated for the origin-destination pair as attributes of travel time and travel cost are dependent on the departure location and the arrival location of the passenger. Furthermore, the utility for a potential trip will be calculated for all three of the selected transport modes. The following utility function is formulated for air transport:

$$U_{OD}^{air} = \text{ASC}^{air} + \alpha \cdot (c_{air} \cdot d_{OD}^{air} + t_{air} \cdot VoT_{air}) + \beta \cdot Safety_{air} \tag{4.1}$$

Similarly, for the utility function calculation of the travel option with High-Speed Rail the following equation was formulated:

$$U_{OD}^{HSR} = \text{ASC}^{HSR} + \alpha \cdot (c_{HSR} \cdot d_{OD}^{HSR} + t_{HSR} \cdot VoT_{HSR}) + \beta \cdot Safety_{HSR} \tag{4.2}$$

Finally, the utility yielded from selecting the Hyperloop as a travel mode is calculated with the following function:

$$U_{OD}^{hyp} = \alpha \cdot (c^{hyp} \cdot d_{OD}^{hyp} + t_{hyp} \cdot VoT_{hyp}) + \beta \cdot Safety_{hyp} \tag{4.3}$$

where subscripts O and D represent an origin and a destination respectively, ASC represents the alternative specific constant for all transport modes. ASC is included in the utility function to include the unobserved attributes in the utility for each transport mode. The inclusion of the unobserved attributes is important to be able to build the choice model realistically and have an accurate representation of the real-life behavior of passengers. VoT represents the Value of Time passengers place on spending an hour on a given transport mode. Value of Time is also referred to as the willingness to pay by

Parameter	Definition	Value	Source
α	Sensitivity of passengers toward generalized transport costs	*-0.02*	[120]
ASC^{air}	Alternative Specific constant for air that corresponds to the error term for the utility	*-5.48*	[2]
ASC^{HSR}	Alternative Specific constant for air that corresponds to the error term for the utility	*-0.8*	[2]
β	Sensitivity of passengers to the safety level parameter	*1.5*	[120]
c_{air}	Travel cost for air transport (€ per km)		Google Flights
c_{HSR}	Travel cost for high-speed rail transport (€ per km)		Google Maps
c_{hyp}	Travel cost for Hyperloop transport (€ per km)		Google Maps
d_{OD}^{air}	Distance between the origin and destination for air transport (km)		Google Flights
d_{OD}^{HSR}	Distance between the origin and destination for high-speed rail transport (km)		Google Maps
d_{OD}^{hyp}	Distance between the origin and destination for Hyperloop transport (km)		Google Maps
t_{HSR}	Travel time for air transport between O-D (hours)		Google Flights
t_{HSR}	Travel time for high-speed rail transport between O-D (hours)		Google Maps
t_{hyp}	Travel time for Hyperloop transport between O-D (hours)		Google Maps
VoT_{air}	The value of travel time for air transport (€ per hour)	*€41.7*	[2]
VoT_{HSR}	The value of travel time for high-speed rail transport (€ per hour)	*€14.3*	[2]
VoT_{hyp}	The value of travel time for Hyperloop transport (€ per hour)	*€11.7*	[2]

Table 4.2: The parameters used in the formulation of the MNL model with their definition, value and sources used.

passengers to save an hour of commute with the given transport mode [11]. The multi-nominal logit models enable the identification of the value of time passengers place on transport modes and are used by policy-makers extensively [2]. α and β are coefficients that are used to include the sensitivity of passengers to the generalized transport costs and safety level of the transport mode, respectively. A detailed overview of the parameters to be used in the Multi-nominal logit model can be found in Table 4.2.

The parameter values and utility functions employed in this study are derived from previous research conducted by scholars in the field of Hyperloop transportation. The determination of alternative specific constants was accomplished by Abouelela et al. (2022) [2] using a stated preference and multinomial logit model. For the purposes of this study, the values of the alternative specific constants will be adopted without modification. Utility models frequently incorporate parameters to account for passengers' sensitivity to variations in different attributes within the utility function. In the formulated utility function, the parameter denoted as α represents the sensitivity towards generalized transport costs, while β signifies the sensitivity to the safety level. Both parameter values have been obtained from the study conducted by Voltes-Dorta et al. (2018) [120], where the parameters were calibrated using real-life modal split data from California, United States. A previous study by Lieshout (2012) also concurred that these values serve as reliable indicators of passenger sensitivity to the respective attributes [72]. The value of α has been calculated as -0.02 and the value of β has been calculated as 1.5.

To convert time into a generalized cost, the willingness-to-pay value (VoT) is multiplied by the travel time. Hence, it is imperative to ascertain the value passengers assign to spending a unit of time in a specific mode of transportation. Abouelela et al. (2022) calculated this value through a stated preference survey. Their findings indicate that passengers value an hour spent in an airplane at € 41.7, an hour spent on High-Speed Rail at € 14.3, and an hour spent in the Hyperloop at € 11.7. Similar to the sensitivity parameters, the values of VoT will be sourced from the study conducted by Abouelela et al. (2022). Travel time and travel cost between an origin-destination are also important parameters in the choice model. The total travel cost of each transport mode is calculated by multiplying the distance between each origin-destination pair with the cost per kilometer. In order to obtain the distance between the origin-destination pair, Google Maps information was used. Hyperloop distances between is origin-destination pair is assumed to be identical to high-speed rail distances in alignment with the assumption that the rights of way will follow existing rail infrastructure. Therefore, the travel time and the cost of travel between an origin and destination need to be clearly known to be able to calculate the utility of passengers. All of the aforementioned parameters will be used to calculate the utility passengers will receive upon traveling between a specific origin and destination. The equations 4.1, 4.2 and 4.3 will be used to calculate the utility of each transport mode.

Probabilistic Mode Choice

Following the calculation of travel utility per mode, the next step in strategic planning is the probabilistic mode choice calculation. The probability of a passenger selecting between the alternatives of air, high-speed rail, or Hyperloop will depend on the utility they will receive for their specific origin-destination pair. The equation detailed in Chapter 3 will be utilized for this purpose. The following equation will calculate the yield of the probability of selecting air transport for an origin and destination:

$$P_{OD}^{(Air)} = \frac{e^{(U_{air})}}{e^{(U_{air})} + e^{(U_{HSR})} + e^{(U_{hyp})}} \tag{4.4}$$

Similarly, the probability that the passenger selects the option to travel with High-Speed Rail will be calculated via the following equation:

$$P_{OD}^{(HSR)} = \frac{e^{(U_{HSR})}}{e^{(U_{air})} + e^{(U_{HSR})} + e^{(U_{hyp})}} \tag{4.5}$$

Finally, the probability that the passengers opt to travel with Hyperloop for any given origin-destination pair will be calculated via the following equation:

$$P_{OD}^{(hyp)} = \frac{e^{(U_{hyp})}}{e^{(U_{air})} + e^{(U_{HSR})} + e^{(U_{hyp})}} \tag{4.6}$$

Given the structure of the Multinomial Logit (MNL) model formulation, the probabilities associated with selecting each transport mode collectively sum up to 1. Consequently, it is not possible for passengers to opt out of traveling altogether for a particular origin-destination pair. To assess the demand for Hyperloop transportation between a specific origin and destination, Equation 4.6 will be utilized to compute the probability that a passenger, journeying from an origin to a destination, chooses Hyperloop as their preferred mode of travel. To determine the overall demand for an origin-destination pair, it is necessary to multiply the probability of selecting Hyperloop by the total number of passengers traveling between the same origin and destination utilizing the alternative modes of air and high-speed rail. It is imperative to possess an origin-destination demand matrix for air and high-speed rail to perform this computation accurately. The result obtained will indicate the total demand for Hyperloop within a particular corridor. This demand volume for each origin-destination pair will subsequently serve as input for the FL-ND problem (refer to Figure 5.1).

4.1.2. The Facility-Location Network Design Problem Formulation

The second part of the Hyperloop's strategic planning constitutes a facility-location network design problem. The model attempts to replicate real-life constraints and objectives of a prospective Hyperloop network design. The main objective of the model is to gain insight into the impact of network design decisions on the key performance indicators of the system. In this model, the network is represented with a graph made up of vertices and edges ($G = (V, E)$). Vertices are a set of predetermined locations (nodes) where a Hyperloop station may be built. The vertices of the graph are also referred to as nodes and are represented by the indices i and j.The edges between the hubs represent the Hyperloop infrastructure that enables the Hyperloop to offer services between the vertices it connects. The vertices of the graph are also referred to as nodes and are represented by the indices i and j within the set $V = \{v_1, v_2, ...v_n\}$ where n represents the number of vertices. Following this formulation of the graph, a 'path' is defined between each origin-destination pair and represented by the index of k within the set of all possible paths between the said pair of vertices where $P_{ij} = \{k_1, k_2, ...k_n\}$. Any path can consist of trips originating from node i to the destination node j and can be consisting of several stops in other nodes. Furthermore, the set P_{ij}^{direct} is defined to consist of all direct connections (edges) between nodes i and j. The set is defined as $P_{ij}^{direct} \subset P_{ij}$, where the direct connections are a subset of all possible paths between two nodes. This distinction has been made to formulate specific constraints in relation to the model's decision variables, which will be described in the subsequent subsections. An overview of the sets and indices of the model can be found in Table 4.3.

Name	Notation	Index in Set	Explanation
Node	$V = \{i_1, i_2, ...i_n\}$	$i, j \in V$	Predetermined origin/destination nodes in the graph
Edges	$P_{ij}^{direct} = \{k_1, k_2, ...k_n\}$	$k \in P_{ij}^{direct}$	Set of edges from origin i to destination j
All Paths	$P_{ij} = \{k_1, k_2, ...k_n\}$	$k \in P_{ij}$	Set of all possible paths between origin i to destination j

Table 4.3: Overview of the sets used in the model and the indices.

In order to illustrate the set definitions more clearly, consider the following example. Let a sample network graph consisting of nodes $V = \{A, B, C\}$ be visualized in Figure 4.3. Suppose that all nodes are connected to each other with edges and the origin node is determined as Node A while Node B is the destination node. Consequently, the set of all paths between the origin node A and destination node B will include path k_1, illustrated in red, and path k_2, illustrated in blue. Hence, the set of all paths between these nodes will be $P_{AB} = \{k_1, k_2\}$. On the other hand, the set of direct paths (edges) will be $P_{AB}^{direct} = \{k_1\}$.

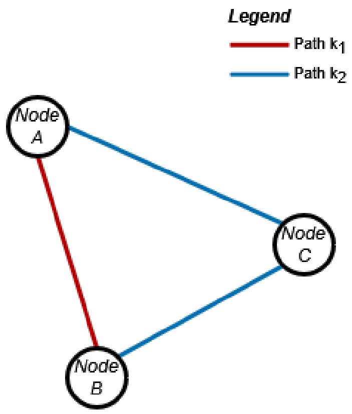

Figure 4.3: A sample network with three nodes and edges.

Assumptions of the Model

The model has been formulated with several assumptions made. These assumptions were made to scope down the problem to the research questions formulated. As a result, some of the real-life constraints of a prospective Hyperloop network have been omitted from the formulation of the problem.

- The characteristics of the prospective Hyperloop hubs have been assumed to be completely identical.
- The technical specifications of the Hyperloop including top speed, acceleration, energy demand, emissions, and capacity are assumed to be homogeneous amongst all pods.
- All infrastructure for Hyperloop is homogeneous, meaning that no matter the geographical constraint, the costs are linear and only dependent on the length of the infrastructure.

- The infrastructure and the hubs have no capacity constraints associated with them.
- The transfer times are identical and assumed to be 15 minutes [87].
- Weather conditions and potential disasters are not considered in this study and have no effect on travelers.
- High-Speed Rail and Air transportation alternatives are available between all pairs of nodes.
- The emissions caused by the construction of Hyperloop infrastructure have not been included in the emissions cost as there is a lack of consistent information. Furthermore, the operational emissions have been set to zero as explained by [87].
- The rights of way are identical to the geographical routes used by existing rail infrastructure.

Following the introduction of the assumptions, the model can be considered to be consisting of three major components. The decision variables, objective functions, and constraints of the model will be introduced in the following subsections.

Decision Variables

The decision variables of the mathematical model are selected as the variables that are commonly used in many facility-location and network design problems as explained in Chapter 3. The notation and definitions are also taken from similar studies in the literature even though various different notations are used as well.

Notation	Indices	Type of Variable	Explanation
z_i	$i \in V$	Binary	The variable representing whether a Hyperloop hub is built in location i
y_{ij}	$i, j \in V$	Binary	The variable representing the decision to built infrastructure (edge) between hubs i and j

Table 4.4: The decision variables of the formulated problem.

Notation	Indices	Explanation
Pen^{stop}	$-$	Utility penalty parameter for having to transfer to another Hyperloop pod in a path.
x_{ijk}	$i, j \in V$, $k \in P_{ij}$	Binary parameter representing that path k between hubs i and j is available
b_{ij}	$i, j \in V$	Binary parameter indicating the existence of at least a path from node i to node j.
e_{ij}^{hyp}	$i, j \in V$	The parameter indicating the emissions per passenger for Hyperloop.
e_{ij}^{air}	$i, j \in V$	The parameter indicating the emissions per passenger for Air transport.
e_{ij}^{HSR}	$i, j \in V$	The parameter indicating the emissions per passenger for HSR transport .
D_{ij}	$i, j \in V$	The parameter indicating the total passenger demand from node i to node j.
$price^{hyp}$	-	The parameter indicating the ticket price (in € per km) for a Hyperloop trip.
$price^{air}$	$i, j \in V$	The parameter indicating the ticket price (in € per km) for an air trip. .
$price^{HSR}$	$i, j \in V$	The parameter indicating the ticket price (in € per km) for a HSR trip.
$dist_{ij}^{hyp}$	$i, j \in V$	The parameter representing the total Hyperloop trip distance (in km) between nodes i and j.
$dist_{ij}^{air}$	$i, j \in V$	The parameter representing the total air trip distance (in km) between nodes i and j.
$dist_{ij}^{HSR}$	$i, j \in V$	The parameter representing the total HSR trip distance (in km) between nodes i and j.
c_{hub}^{hyp}	$-$	Capital Costs (in million €) towards construction of a single Hyperloop hub.
c_{inf}^{hyp}	$-$	Capital Costs (in million €) towards the construction of a kilometer of Hyperloop infrastructure.
B	$-$	Total budget available for hyperloop infrastructure.

Table 4.5: The parameters included in the formulation of the problem.

The decision variables of the formulated problems are identical to the key decision variables identified in the review of the literature. (Chapter 3). The overview of the decision variable for this FL-ND problem formulation for Hyperloop can be found in Table 4.4. The first decision variable, z_i, represents the hub location decision and is a binary variable. A detailed description of the variable can be found in Equation

4.7. The second decision variable, y_{ij} represents the line planning decision. Similar to the first variable it is binary. A detailed description of the variable can be found in Equation 4.8.

$$z_i = \begin{cases} 1, & \textit{if node i is selected to be a Hyperloop hub} \\ 0, & \textit{otherwise} \end{cases} \tag{4.7}$$

$$y_{ij} = \begin{cases} 1, & \textit{if node i and node j are connected with infrastructure} \\ 0, & \textit{otherwise} \end{cases} \tag{4.8}$$

Objective Functions

The problem has been formulated as a multi-objective optimization problem. Therefore, the model has several objective criteria to maximize and/or minimize. Commonly, facility-location network design problems have the main objective of minimizing total transportation costs [21]. However, the literature review conducted in Chapter 2 and Chapter 1 has revealed additional motivations behind the conceptualization of Hyperloop. Firstly, in alignment with the comparative advantages of the Hyperloop technology, travel cost and travel time attributes are potentially more favorable for the passengers. As discussed in detail in Chapter 3, mathematical formulation of these choices can be made with RUM and MNL models with the concept of utility. Hence, one of the first objectives of this problem is to maximize the utility received by the passengers. The corresponding objective function can be found in Equation 4.24. Previously, the necessity to facilitate a modal shift towards more sustainable modes of transportation has been emphasized. In order to assess whether a modal shift can be achieved with a specific network design, the probability of Hyperloop usage has been selected as the second objective function which can be found in Equation 4.25. Third objective function selected for this model is related to the total emissions emitted by the transportation system. In the previous chapters, the importance of emission reductions has been emphasized in alignment with the European Green Deal [31]. Hyperloop has the potential to significantly curb emissions and therefore one of the objectives has been selected to reflect this potential (Equation 4.26). Lastly, the economic potential of Hyperloop has been evaluated from the supply side. The fourth objective is related to the revenue of a potential operating company. (Equation 4.27). The overview of parameters included in the formulation of the objective functions can be found in Table 4.5.

Objective 1: Utility Maximization

$$\max \quad Pen^{stop} \cdot \sum_i \sum_j \sum_{k \in P_{ij} \setminus P_{ij}^{direct}} x_{ijk} \cdot U_{ij}^{hyp} \quad + \quad \sum_i \sum_j \quad y_{ij} \cdot U_{ij}^{hyp} \tag{4.9}$$

The first objective function aims to maximize the total utility the passengers receive by selecting Hyperloop in their trips. The utility function itself has been formulated in Section 4.1.1. The first part of the objective is related to the indirect Hyperloop paths available between origin i and destination j. The terms have been separated to include a penalty parameter for the indirect paths as it is undesirable for the passengers. The second part of the objective function is the utility received by passengers traveling via Hyperloop directly to their destination.

Objective 2: Probability of Usage Maximization

$$\max \quad \sum_i \sum_j \quad b_{ij} \cdot P_{ij}^{hyp} \tag{4.10}$$

Objective Function 2 aims to maximize the total probability that passengers will select Hyperloop in their travel itineraries. The network design will be constructed with the objective of making Hyperloop the most attractive option for passengers. The probability function depends on the utility function for not only Hyperloop but is also dependent on the utility functions for HSR and air transport. The extended formulation of the probability function, P_{ij}^{hyp}, can be found in Section 4.1.1.

Objective 3: Emission Minimization

$$\min \sum_i \sum_j \quad (e_{ij}^{hyp} \cdot D_{ij} \cdot P_{ij}^{hyp} \cdot b_{ij} \quad + \quad e_{ij}^{air} \cdot D_{ij} \cdot P_{ij}^{air} \quad + \quad e_{ij}^{HSR} \cdot D_{ij} \cdot P_{ij}^{HSR}) \tag{4.11}$$

Objective Function 3 aims to minimize the total carbon-dioxide emissions of the transportation system. The first term in the objective function tracks the emissions of the Hyperloop system. The second and the third terms are the total emissions emitted by air transport and rail transport, respectively. The emission factors are taken per passenger per kilometer, therefore they are multiplied by the total demand, distance, and probability of usage.

Objective 4: Revenue Maximization

$$\max \quad price^{hyp} \cdot \sum_i \sum_j \quad (D_{ij} \cdot P_{ij}^{hyp} \cdot b_{ij}) \tag{4.12}$$

Objective function 4 calculates the potential revenue the Hyperloop operating company will receive. Needless to say, the total revenue will depend on the demand for Hyperloop and the ticket price per passenger. Hence, the terms $price_{ij}^{hyp}$, D_{ij} and P_{ij}^{hyp} are included in the function. This function will give insight into the feasibility of the Hyperloop system and whether it will be a viable-profit-driven transport business.

Constraints

Constraints of the model ensure the feasibility of the problem both in the sense to have computational consistency as well as being as close to reality as possible. The constraints have been adapted from similar infrastructure decision problems in the literature with special emphasis on rail-based network design. This decision is based on the similarities of Hyperloop infrastructure with rail-based transport modes. This subsection will introduce the constraint and provide the context behind them. The overview of parameters included in the formulation of the constraints can be found in Table 4.5

Constraint 1: Hub Construction Logical Constraint

$$y_{ij} \leq z_i \qquad \forall \quad i,j \in V \tag{4.13}$$

$$y_{ij} \leq z_j \qquad \forall \quad i,j \in V \tag{4.14}$$

Constraint 1 bounds the problem solution in order to have a logically correct solution. It ensures that in order for a connection to be built between the nodes i and j, both node i and node j need to be selected as hubs. Thus, preventing a scenario where infrastructure exists without arrival and destination hubs existing.

Constraint 2: Budget Constraint

$$c_{hub}^{hyp} \cdot \sum_i (z_i) + c_{inf}^{hyp} \cdot \sum_i \sum_j (y_{ij} \cdot dist_{ij}^{hyp}) \leq B \qquad \forall \quad i,j \in V \tag{4.15}$$

Constraint 2 is related to the total capital costs to set up the Hyperloop network. To achieve economic feasibility, the capital costs of the entire project represent an important decision-making aspect. The first term of the constraint is to track the costs of the construction of Hyperloop hubs at a location. The second term is related to the routing decision and keeps track of the infrastructure costs associated with the decisions made regarding the network design. The constraint ensures that the cost of the network decision cannot exceed the budget for the project denoted by B.

Constraint 3: Exemption of Intra-zonal Routes

$$y_{ii} = 0 \qquad \forall \quad i, j \in V, \tag{4.16}$$

One of the assumptions of the model is that it is not possible to have Hyperloop travel within the same node. This is due to the technical specifications of Hyperloop. The system requires a distance of 250 kilometers for Hyperloop to be able to accelerate and decelerate to its operational speed. Distances shorter than this threshold makes Hyperloop unable to compete with other transport modes [87]. Therefore, in the model, it is not possible to create routes within the same node which represents a hub.

Constraint 4: Symmetry of Infrastructure

$$y_{ij} = y_{ji} \qquad \forall \quad i, j \in V, \quad i \neq j \tag{4.17}$$

This constraint ensures the continuity of the network infrastructure. Similar to rail infrastructure, Hyperloop lines will be able to run the identical route in opposite directions. Therefore, if a decision is made to construct a route between two nodes, the symmetrical line will also be built allowing for two-way trips.

Constraint 5: Connection of Hubs

$$\sum_{j} \quad y_{ij} \geq z_{ii} \qquad \forall \quad i \in V \tag{4.18}$$

Constraint 5 is related to the connection of hubs. It ensures that if a node is selected as a hub, at least one outgoing connection must exist to another hub. Otherwise, the hub will not be operational and the graph will be disconnected. Breach of this constraint would mean that it might not be possible to travel to a Hyperloop hub.

Constraint 6: Existence of Hubs in a Path

$$x_{ijk} \leq z_{ii} \qquad \forall \quad i, j \in V, k \in P_{ij} \tag{4.19}$$

$$x_{ijk} \leq z_{jj} \qquad \forall \quad i, j \in V, k \in P_{ij} \tag{4.20}$$

Constraint 6 is related to the paths available as a result of the network design. A path is described as the route taken by the passenger to reach destination j from origin i. This constraint ensures that a path only exists if the hubs are opened. This constraint further ensures that the paths offered to the prospective passenger represent the network design. Therefore, the key performance indicators related to passenger choices can be analyzed correctly.

Constraint 7: Path must be offered if Connection exists

$$\sum_{k} x_{ijk} \leq M \cdot b_{ij} \qquad \forall \quad i, j \in V, \quad i \neq j \tag{4.21}$$

$$\sum_{k} x_{ijk} \geq M \cdot (1 - b_{ij}) \qquad \forall \quad i, j \in V, \quad \text{for} \quad i \neq j \tag{4.22}$$

Constraint 7 is also related to the paths available for the passengers to be chosen. This constraint is formulated in order to ensure that a path is only offered to the passengers if the corresponding origin-destination pair is connected via at least a single path (directly or indirectly). Otherwise, the path is not available for the passengers to travel on. This constraint utilizes a big M method to ensure an if and only if scenario, where a path is only offered if and only if a route exists. For this purpose, a binary variable b_{ij} is introduced. Furthermore, this constraint allows the paths to be categorized into direct and indirect routes connecting an origin-destination pair as it will be an important distinction for the output of the model.

Constraint 8: Existence of a Direct Path

$$x_{ijk} = y_{ij} \qquad \forall \quad i, j \in V, k \in P_{ij}^{direct} \tag{4.23}$$

Constraint 8 is formulated to ensure that a path without transfers is available between origin i and destination j if hubs i and j are connected to each other directly. Otherwise, the direct path is not available. The set P_{ij}^{direct} represents the set of direct paths between nodes i and j.

Constraints 9: Multi-Objective Constraints

$$\sum_i \sum_j \quad x_{ijk} \cdot Pen^{stop} \cdot U_{ij}^{hyp} \quad + \quad \sum_i \sum_j \quad y_{ij} \cdot U_{ij}^{hyp} \leq objBound_{Utility} \tag{4.24}$$

$$\sum_i \sum_j \quad b_{ij} \cdot P_{ij}^{hyp} \leq objBound_{Probability} \tag{4.25}$$

$$\sum_i \sum_j \quad (e_{ij}^{hyp} \cdot D_{ij} \cdot P_{ij}^{hyp} \cdot b_{ij} \quad + \quad e_{ij}^{air} \cdot D_{ij} \cdot P_{ij}^{air} \quad + \quad e_{ij}^{HSR} \cdot D_{ij} \cdot P_{ij}^{HSR}) \geq objBound_{Emissions} \tag{4.26}$$

$$\sum_i \sum_j \quad price_{ij}^{hyp} \cdot D_{ij} \cdot P_{ij}^{hyp} \cdot b_{ij} \leq objBound_{Revenue} \tag{4.27}$$

The constraints are related to the property of the model being a multi-objective optimization model. Chapter 3 has discussed the Multi-Objective Optimization models more in detail. Constraint 10 includes all of the objective functions with the right-hand side of all functions being upper/lower bounds for the values. The ϵ-constraint method is utilized as formally described in Equation 3.2. According to this method, the model will be run to optimize each objective separately. The solutions obtained will be Pareto Optimal solutions and the values of the objectives will constitute the right-hand side values for other objective types. For instance, if the model is run to optimize Utility, other objective function values will be acting as constraints to provide upper/lower bounds. Since the emissions objective function is the only minimization objective, the representative constraint has the opposite sign compared to the other constraints. $objBound_{Utility}$,$objBound_{Probability}$ $objBound_{Emissions}$ and $objBound_{Revenue}$ represent these values. Therefore, the model has to be adjusted prior to running the model for a specific objective.

Output of the Model

The output of the model has the main objective of enabling the assessment of the key performance indicators. The key performance indicators are in alignment with selected objective functions. The main output of the model includes the values of the decision variables. The selected hub locations as well as the connections of the hubs are outputted as per their values. The resultant network is subsequently visualized to have a better understanding of the network topology. A general overview of the outputs.

Aside from the objective function values, there are several characteristics of interest in the model. These parameters might be indicative of the consequences a Hyperloop network might have on the global transportation industry. The available paths to travel (x_{ijk}) values are outputted to have an overview of the potential modal shift in significant transport corridors. Similarly, the average probability of Hyperloop usage is a parameter to give insights into the competitiveness of Hyperloop as a transport mode. The perspective of the operator company is also considered in the model. The total capital costs required for the network design generated are of critical importance to the stakeholders. The annual operation costs and the potential revenue as a result of the generated solutions are also included in the study to include temporality in the cost-benefit discussion. The years needed to break even are calculated to give an overview of the feasibility of the prospective Hyperloop network design.

This chapter has outlined the formulated demand analysis model and the facility-location network design problem for a Hyperloop network. The theoretical background has been introduced as well as the mathematical formulation of the problem which has been adjusted to fit the characteristics of Hyperloop. Four different objective functions have been formulated to assess the performance of a potential Hyperloop network design. The key performance indicators have been outlined with the potential solution pool of the model described. The subsequent chapter will use a case study to further exemplify the model.

5

European Case Study

The formulated facility location-network design problem has been placed within the context of a new Hyperloop infrastructure within Europe. The European Union and its subsidiaries have been exploring the potential policy measures to facilitate the modal shift from less advantageous transport modes to more advantageous modes. This case study aims to provide a basis to assess whether a European Hyperloop network will be able to foster change for good. The case study aims to evaluate the feasibility of constructing a Hyperloop network across key European cities and to assess the potential economic and environmental impacts of implementing the Hyperloop system. Thus, recommendations will be provided to the policymakers and stakeholders involved in the development of a Hyperloop network. This chapter is organized as follows: Section 5.1 will introduce the selected nodes and the argumentation behind the decisions. Section 5.2 will be about the required data for the case study and the sources of such data. The technological specification of modes will be introduced in section 5.3. Lastly, section 5.4 will introduce the experimental set-up of the case study.

This chapter is organized as followed: Section 5.1 will introduce the relevant countries that are selected as candidate nodes in this study. Section 5.2 will introduce the demand data used in this case study while Section 5.3 will discuss the assumptions made regarding the technical specifications of the transport modes. Finally, the chapter will conclude with Section 5.4 where the experimental set-up is introduced to test the model further.

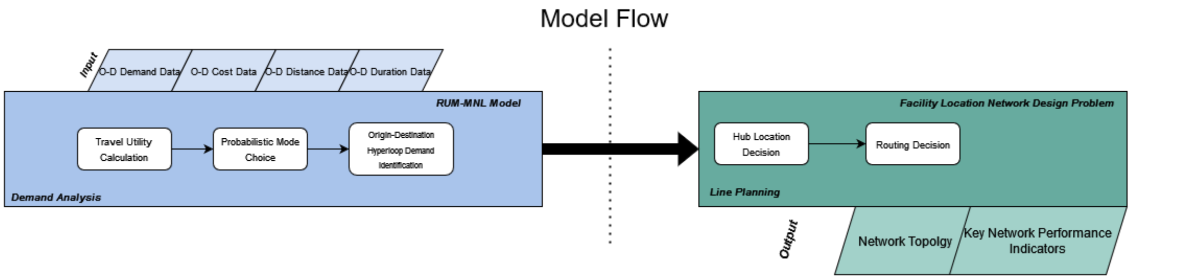

Figure 5.1: The order of operations and the flow of the model.

5.1. Selection of Nodes

The problem formulation has outlined in Chapter 4 that the set of nodes correspond to the potential locations for a Hyperloop hub to be constructed. The following subsections describe the filtering methodology for the selection of nodes.

5.1.1. NUTS Specification and TEN-T Network

In order to conduct analytical filtering, European Union data from Eurostat was utilized as the main source of statistical data. Eurostat uses a classification method referred to as ”NUTS” (Nomenclature of territorial units for statistics) classification. This classification has been created in 1999 in order to ensure access to harmonized data and act as a support tool for policymakers to target specific economic regions for policy interventions. NUTS classification has three hierarchical distinctions referred to as NUTS1, NUTS2, and NUTS3 [40]. The specification is based on economic growth criteria such as the GDP of the region as well as population statistics and serves as a basis for policy-makers to scope their interventions. For instance, the TEN-T Network, introduced in Chapter 1, has been planned with NUTS3 regional specification. Therefore, this case study is also based on the NUTS specification as the base layer. The geographical scope of the NUTS region can be found in Appendix B. Both the NUTS classification and the planned TEN-T network include all European Union member states in them. The TEN-T Network map can be found in Figure 5.2. In total, 27 countries are included in the TEN-T network map.

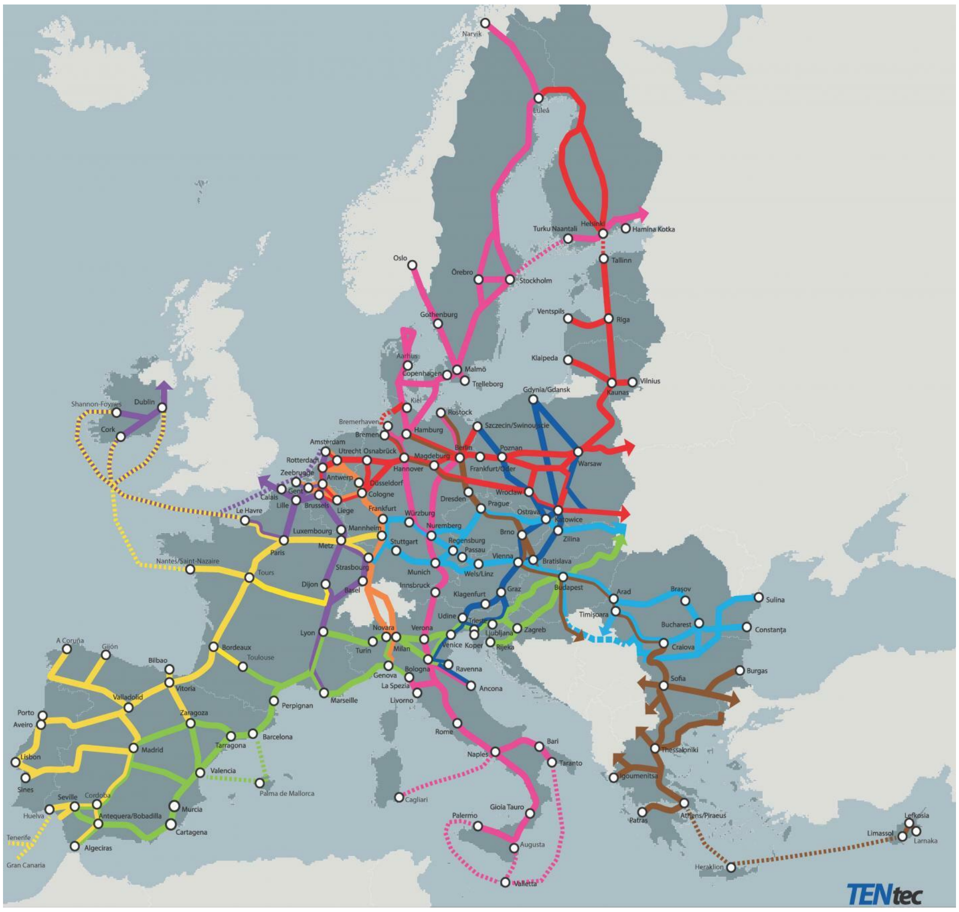

Figure 5.2: Future Projections of Total Energy Demand in Transport per mode and their shares. Source:Directorate-General for Mobility and Transport, European Commission

However, there are certain limitations to including every single member state in the study. First, the technological properties of Hyperloop and the uncertainty around the proof of concept for the technological design make it unclear to predict whether some connections will be available. For instance, the research and full-scale tests are not clear regarding the structural integrity of the infrastructure. There might be skepticism toward whether the pylons that carry the entire Hyperloop tubes and pods will be safe enough to construct over bodies of water. Hence, European destinations in the TEN-T network that are not fully connected via land are excluded from the scope of this study.

Furthermore, due to the acceleration and deceleration of the Hyperloop to achieve cruising speed, the

Figure 5.3: Short-haul flight routes that can be replaced by a maximum 2.5 hour rail-based trip

Figure 5.4: Short-haul flight routes that can be replaced by a maximum 4 hour rail-based trip

distance of the route has great importance. Technical studies indicate that the distance must be at least 200 km between the origin and the destination of the travel. Otherwise, the technology is unable to reach the cruising speed of 1000 kilometers per hour. Failure to reach the cruising speed will strip Hyperloop of its critical comparative advantage over other modes of transport and it will not be an attractive option. Passengers would be unlikely to select a new transport mode that potentially has no advantages over existing transport options but rather has significant concerns associated with it. Furthermore, policymakers and/or investors would be unwilling to dedicate immense resources to a Hyperloop line that lacks transportation time advantages. In order to ensure that Hyperloop is a competitive mode within the scope of this research, distances shorter than 200 kilometers have been excluded.

The transformative potential of Hyperloop technology has been discussed in detail in Chapter 2. Hyperloop has been conceptualized to be a competitor to short-haul flights by emitting fewer emissions, and a competitor to HSR by having shorter travel times. This research aims to explore the modal shift from the competing transport modes to Hyperloop. Therefore, all three transport mode alternatives must be viable for passengers to observe the modal split. In order to correctly answer the research questions, routes where all three transport modes will be included as potential Hyperloop routes. European Commission has conducted a study to identify flight routes in which short-haul flights can be reduced by a rail-based trip with a maximum duration of 4 hours and a maximum duration of 2.5 hours (See Figure 5.4 and Figure 5.3). The purpose of this study indicates that in order to facilitate the modal shift from air, these passenger travel corridors could be beneficial starting points for policymakers [27] .

The visualization of the transport corridors where short-haul flights and rail-based modes compete reveals that a high concentration of these trips is done in north-western Europe. This can be attributed to the lack of electrified rail infrastructure due to a lack of investment and geographical constraints in Eastern Europe. This case study will use utilize these corridors to be the set of potential Hyperloop nodes to be considered. Figure 5.4 includes the following member states:

- Finland
- Sweden
- Norway
- United Kingdom
- the Netherlands
- Belgium

- Luxembourg
- France
- Spain
- Portugal
- Italy
- Switzerland
- Austria
- Poland

The TEN-T network does not directly consider implications for countries that are not an EU member state and thus, the United Kingdom, Switzerland, and Norway are excluded from the study. Finland and Sweden were also excluded from consideration as a link that would require infrastructure to be built upon bodies of water due to the aforementioned structural ambiguity.

Chapter 3 has discussed the importance of having the passenger demand data for each origin-destination pair included in the formulation of such a problem. Demand analysis has proven to be extremely difficult with the lack of such data which will be used as input for the facility-location network design problem. Eurostat and the national statistics institutes were searched to obtain such data for the member states included in the study. Unfortunately, the author could not obtain the necessary data for certain member states. The traffic flow data was either on an aggregate level or was not publicly available. Therefore, Luxembourg, Poland, Portugal, and Austria were also excluded from the case study. An overview of the excluded countries for the purposes of this case-study and the main reason behind their exclusion can be found in Table 5.1.

Country	Reason for Exclusion
Finland	Geographical Constraints
Sweden	Geographical Constraints
Norway	Not Included in TEN-T Network
United Kingdom	Not Included in TEN-T Network
Luxembourg	Lack of Comprehensive Data
Portugal	Lack of Comprehensive Data
Switzerland	Not Included in TEN-T Network
Austria	Lack of Comprehensive Data
Poland	Lack of Comprehensive Data

Table 5.1: The countries that were excluded in this cases study and the reason behind the exclusion

As a result of the pruning of countries considered, the remaining countries of interest for the case study are the Netherlands, Belgium, France, Germany, Spain, and Italy. The sources and the structure of the origin-destination traffic flow data matrices for both air and rail modes will be discussed in the subsequent sections of this chapter.

5.1.2. Geographical Location of Nodes

The member states that will be included in the case study has been identified. However, there need to be precise locations of potential hubs within each member state to be able correctly to identify the routes and the parameters that will significantly influence the output of the model. This subsection will discuss and provide an argumentation for the selection of the geographical location of the nodes.

TEN-T core network aims to connect the major metropolitan areas of the European Union and identifies that the capital cities are vital parts of the core network to be constructed. The economic potential as well as the increasing trends of urbanization in capital cities result in increased demand for transport connectivity. Due to Hyperloop being a novel technology, there are contrasting opinions on the location of hubs. The two options would be to either place them within central locations in a city to make Hyperloop more accessible. However, this could negatively affect the environment and society as there are concerns about land use, noise, congestion, and visual pollution. Constructing Hyperloop hubs on the edges of metropolitan regions similar to airports could be the other option. The connectivity of Hyperloop systems might be harmed with this decision and multi-modal access to the hubs might be required. Nevertheless, there are not any existing hubs to assess the effects on mode choice. For the purposes of this study, the geographical centers of each capital city within the selected countries have been selected to serve as a compromise solution.

In order to identify the geographical location of each capital city, latitude and longitude information, is required. These values were identified via an API tasked to calculate the exact location of the capital cities that were identified for the study. OpenCageData API has been utilized for this purpose [93] by the German-based company OpenCage GmbH.The API needs the ”City” and the ”Country” information to be inputted in order to have the default output of the city center. The API is also capable of calculating the distance between any two locations given that their latitude and longitude information are known. The results of the API were verified further by Google Maps data. The verification was done manually for each origin-destination pair. The main objective was to identify the distance connecting the pair with rail-based infrastructure as it is assumed that Hyperloop will be following the existing rights of way. The results were consistent and therefore, the geographical data was used as an input.

5.2. Demand Specification

Subsequent to the identification of the set of nodes to be considered, another key aspect is to identify to total demand data. The demand data needs to be in the form of an origin-destination matrix in order to be used in the utility calculation for each origin-destination pair across the transport modes selected for this study. Historical data regarding the traffic flow from an origin to a destination has been used often in the related studies in the literature as a good indicator of demand. This study follows the same pattern and replicates the usage of traffic data for demand analysis similar to the study of Voltes-Dorta et al. (2018). [120]

In order to observe the substitution effect with Hyperloop becoming prevalent, the origin-destination demand data for both air and rail-based transport is necessary. The main source for the origin-destination demand has been selected as Eurostat. The data is collected by Eurostat annually and voluntary by nations to participate. The air passenger transport between reporting countries data in the form of a matrix has been obtained from the Eurostat database [33] with the online data code AVIA-PAOCC. Through filtering the data, the year 2019 was selected to be the basis. This selection is based on the fact that the annual data for 2021 and 2022 were incomplete at the time of writing this report. The data for 2020 is skewed due to the COVID-19 pandemic and therefore is not chosen to have an accurate model of the demand. The incomplete data for the country of Italy has been completed by the publicly available data for the National Statistics Institute of Italy [62].

The origin-destination traffic flow data for rail transport between countries has been searched on the Eurostat database. The rail demand data has been split into two to distinguish between the incoming and outgoing passenger flow. The online data code for these databases is RAIL-PA-INTGONG and RAIL-PA-INTCMNG [114, 115]. The data for the rail demand has been combined in a single matrix for the purposes of this model.

5.3. Technological Specifications of Transport Modes

The technological specification of the transport modes has direct effects on the model. The specifications are used as parameters in the model which are direct inputs. The utility received by the passengers for choosing to travel with any of the transport modes is dependent on the speed, cost, and safety of the modes. Therefore, accurate representation is vital to have a realistic output for the model. The technological specifications used in the model will be introduced per transport mode. An overview of the parameters that are used within the model can be found in previously introduced Table 4.2 and

Parameter	Definition	Value	Source
e_{air}	Carbon dioxide emissions of air transport (grams per passenger per km)	*90*	[55]
e_{HSR}	Carbon dioxide emissions of HSR transport (grams per passenger per km)	*40*	[55]
e_{hyp}	Carbon dioxide emissions of Hyperloop transport (grams per passenger per km)	*0*	[87]
c_{hub}^{hyp}	Capital costs of a Hyperloop hub construction (million €)	*115.83*	[116]
c_{inf}^{hyp}	Capital costs of a Hyperloop infrastructure construction (million € per km)	*26.72*	[116]

Table 5.2: The parameters used in the formulation of the MNL model with their definition, value and sources used in addition to the parameters in Table 4.2.

Table 5.2 showcasing the additional parameters.

5.3.1. Air Transport

The critical technological attributes for air transport include the mode-specific characteristics of completing a trip. Needless to say, the parameters are dependent on the origin-destination pair. Travel time and travel cost information is required in a matrix structure for all selected origin-destination nodes. In order to obtain the travel duration information the database for the company Skyscanner was utilized [113]. The duration of flights from and to the selected nodes was manually recorded in a matrix form to be able to have a data frame structure. The data was cross-verified through Google Flights. There were no discrepancies observed. Similarly, the ticket costs per passenger are a required data set. An analogous approach was used to obtain such data. Skyscanner and Google Flights information was used and cross-verification was conducted. It is important to note that plane ticket prices are often volatile depending on the location, time of the year, and saturation. These differences are not expected to have major effects on the model. Hence, the average price was considered a compromise and suitable solution for data usage in this case study.

The carbon-dioxide emissions for the trip are another important parameter for the emission minimization objective of the model. The emissions of a flight are also non-constant. The number of passengers on the flight, and the model of the airplane are factors that contribute to the emissions of a trip. However, the international council for clean transportation has indicated that an average commercial flight emits around 90 grams of carbon dioxide per passenger per kilometer [55]. This value has been used as a constant parameter for all origin-destination pair flights in the case study. Value of Time and Alternative Specific constant values are kept as indicated previously in Table 5.2.

5.3.2. High-Speed Rail

The attributes necessary for the model to function as intended are similar to the attributes described for air transport. First, the travel distance and travel cost data were obtained in an identical manner. The database of the company "omio" was utilized to access travel data for the selected origin-destination pairs [8]. The duration and cost values were cross-referenced using the Google Maps database. Ticket prices have differences according to the season, date of purchase, and the saturation of the market. Once again, an average value was considered for all ticket prices for High-Speed Rail between the origin-destination pairs.

Even though it is more environmentally friendly than air transport, High-Speed Rail systems also emit carbon dioxide during their operations. The exact emission factor varies per the system properties, technological capabilities, and saturation of the system. However, for the purposes of this case study, an indicative average value has been selected. The international council for clean transportation has outlined the average carbon-dioxide emissions of High-Speed Rail as 40 grams per passenger per km [55].

5.3.3. Hyperloop

In order to predict a modal split, several attributes of Hyperloop are necessary. First, identical to the previous two transport modes, the travel costs and travel time information are necessary. Due to the fact that there is not an operational Hyperloop facility as of writing this report, there is ambiguity around the capital and operational costs of a Hyperloop system. As a result, the ticket price per passenger to make the system profitable is currently unknown. In the initial concept design, Elon Musk suggested a ticket price of $20 for a trip between San Francisco and Los Angeles. Nonetheless, this suggestion has received criticism due to the fact that it will not be able to cover the operational costs of the system. The price to use Hyperloop for passengers will be a critical factor in the adoption of the transport mode. Consequently, the ticket price of Hyperloop will be used as a variable to be tested in the model and further information about the scenarios will be described in Section 5.4.

The travel times are also unknown at this moment in time, as there are varying design concepts that aim to reach different cruising velocities. This study has assumed that the cruising velocity of a Hyperloop pod will be 1000 km/h. To calculate the travel duration for each origin-destination pair, the distances between the node of departure and arrival are necessary. Another assumption regarding the infrastructure of Hyperloop was to construct the Hyperloop tubes over existing rights of way. For simplicity, this case study will assume that the distances Hyperloop will travel will be identical to those of High-Speed Rail for each of the origin-destination pair. Finally, the travel time will be calculated for each trip by dividing the distance by the cruising speed of the Hyperloop.

Chapter 2 has identified the operational emissions of Hyperloop as a key strength. This model will aim to observe the reduction in emissions (or lack thereof) as a result of a modal shift toward the new transport mode. In theory, Hyperloop does not emit any carbon dioxide into the atmosphere through its operation. Accordingly, this case study will assume that Hyperloop does not have any emissions. On the other hand, the capital costs for the infrastructure have been identified as a potential failure factor. The mode-specific requirements of the system deem the construction costly. This case study will base the parameters of hub construction costs and infrastructure costs on the study of Taylor et al. (2016) [116]. Furthermore, in order to observe the feasibility of the project, the operational costs are considered in the case study. The estimations of the annual operational costs for a prospective Hyperloop system have been taken from the feasibility study of Taylor et al. (2016) [116]. The Value of Time information has been taken from the study of Abouelela et al. (2022) [2]. An overview of all parameters, values and sources can be found in Table 5.2.

5.4. Experimental Set-Up

The model formulation has been discussed and the scope of the case study has been introduced. The parameters and variables to be used in the model have been explained. This section will introduce the experimental set-up of the study in order to be able to provide answers for the main research question and the sub-questions. An overview of the designed experiments can be found in Table 5.3. The experiments can be categorized with their main factor for the sensitivity analysis to be conducted. These categories are ticket price, safety perception, and policy interventions. The following subsection will discuss the experiments in more detail.

5.4.1. Baseline Experiment

The baseline experiment is created to have an overview of the initial performance of the model. The output of the initial network will provide insights into the behavior of the formulated model. Furthermore, the baseline experiment output will be used as a benchmark in order to assess the key performance indicators of the other scenarios. In the baseline experiment, the ticket price is set to €0.1 per kilometer. This price level has been selected to reflect the findings of Borghetti (2023) [10]. The safety perception has been set to be on the same level as air transport. None of the policy interventions are included in the baseline experiment. The baseline experiment further inspects the iterative expansion of the network.

5.4.2. Ticket Price

The ticket price experiment aims to understand the sensitivity of the model toward the costs incurred by the passengers upon choosing the use Hyperloop in their trips. The ticket price will affect the utility received by the passengers of Hyperloop and may make other transport modes more attractive or may make Hyperloop more attractive. The ticket price will further determine the revenue of the Hyperloop operating company. The revenue will be compared to the annual operation costs and the capital costs to determine the break-even point of the system. The experiment is conducted in three different scenarios. In Scenario T1, the price for Hyperloop is set to 0.05 euros per kilometer traveled. This price level is consistent with the price level suggested by Elon Musk in the initial concept of Hyperloop [87]. In Scenarios T2 and T3, the price level for Hyperloop has been increased to €0.1 per kilometer and €0.2 per kilometer, respectively. This experiment aims to provide a guideline for the pricing strategy of a prospective Hyperloop system.

5.4.3. Safety Perception

Safety perception has been identified as a critical attribute of Hyperloop acceptance in previous studies [2]. The design of Hyperloop has not been finalized and there are concerns that exist about the safety of the system for human use. Therefore, public perception is expected to have important consequences on the adoption of Hyperloop. Due to the lack of test facilities to conduct experiments with passenger transport, it is difficult to quantify safety for a transportation mode that is not operational. Therefore, a comparative index-based method has been generated. In the model, the safety perception of air transport has been set as 1, while the safety perception of the High-Speed Rail has been set by the double of air transport as 2. This experiment will build on the study by Abouelela et al. (2022) in order to observe the possible effects of Hyperloop safety perception on the demand for Hyperloop. For this purpose, three scenarios have been created. Scenario S1 assumes that the safety perception of Hyperloop is significantly lower than the perception of safety for flights. In Scenario S1, the safety perception of Hyperloop has been set to 0.5. Scenario S2 assumes that the safety perception of Hyperloop is on par with the safety perception of taking a flight. Lastly, in Scenario S3, the public perception of Hyperloop is that the transport mode is safer than air transport and Hyperloop is as safe as High-Speed Rail with the safety perception variable being set to 2.

5.4.4. Policy Interventions

Chapter 1 has introduced the policy outlook to facilitate modal shift in the upcoming years within the European Union. The existing policy interventions have resulted in positive societal change. However, there exist undesirable situations in the European transportation sector. For instance, the reduction in emissions, whilst being positive, is not substantial enough to reach the European Green Deal goals. Henceforth, the national and federal authorities are in the process of drafting legislature to come up with more efficient policy interventions. It is expected that the European Commission will release further incentives through additional policies. The policy interventions experiment aims to anticipate some of the potential policy interventions in order to assess their effectiveness toward having the intended impacts on the transportation sector. Three such policy interventions are designed for the purposes of this case study. First, Scenario P1 considers an extreme action taken by the European Comission. In this scenario, all short-haul flights that are shorter than 3 hours are banned. For the origin-destination pairs selected for this case study, this results in air transport being completely unavailable for the passengers. The choice model is reduced to only two alternatives of Hyperloop and High-Speed Rail. Scenario P2 considers an additional tax on short-haul flights within European destinations. Therefore, the ticket prices for all air transport alternatives are increased to double the travel costs for passengers. Scenario P3 makes the assumption that authorities invest resources into positively influencing the Hyperloop. Testing facilities, infrastructures, and awareness campaigns are utilized in an attempt to facilitate modal shift. In this scenario, additional demand for Hyperloop is generated through a change in people's tastes and preferences. Therefore, the Alternative Specific Constant for air transport as well as the High-Speed Rail are reduced by a factor of -1.

This Chapter has introduced the case study formulated with the purpose of testing the generated problem. The data requirements and sources for the variables, as well as the parameters of the model,

Category	Scenario Name	Effect
Baseline	Baseline (T2 & S2)	-
Ticket Price	T1	Ticket Price for Hyperloop set to €0.05 per km
	T3	Ticket Price for Hyperloop set to €0.2 per km
Safety Perception	S1	Hyperloop is perceived as less safe than air transport
	S3	Hyperloop is perceived as safer than air transport
Policy Intervention	P1	Short-haul flights are banned in Europe
	P2	Short-haul flight tax imposed in Europe
	P3	Hyperloop perception positively influences demand

Table 5.3: The categories, codes and the effects scenarios have for the experiments designed.

have been outlined. The argumentation was given toward scoping the case study. Furthermore, the experimental set-up has been discussed with the variables and the scenarios being introduced. The subsequent Chapters 6 and 7 will discuss the results and conclusions to be had from the study, respectively.

6 Results

The formulated problem and the experiments designed to potentially answer the research question were implemented in Python 3.8.8. The Gurobi version 10.0.0 package was used to formulate the mathematical model in Python. The interface environment utilized for the implementation is Spyder version 4.2.5. All of the experiments were run using a personal computer with the computational hardware of Intel(R) Core(TM) i7-10750H CPU @ 2.60GHz and 32 GB RAM. This chapter will introduce the results and the values of the key performance indicators for the model. The outcomes of the baseline experiment and the results of the experiments will be compared. Section 6.1 will introduce the results of the baseline experiment. Section 6.2 will introduce the results obtained from the ticket price experiments. Section 6.3 will detail the outcome of the safety perception experiments. Section 6.4 will discuss the results of policy intervention scenarios and section 6.5 will discuss the main takeaways of the scenario results.

6.1. Baseline experiment

The baseline experiment has been conducted to observe the initial performance of the model. The initial conditions were set as explained in Section 5.4. The values of the parameters used in this experiment can be found in Table 6.1 Furthermore, the model was run with consideration of all four of the objective functions determined. The results show that a fully operational Hyperloop network has been built in accordance with the parameterization of the constraints.

Parameter	Definition	Value
α	Sensitivity of passengers toward generalized transport costs	*-0.02*
ASC_{air}	Alternative Specific constant for air that corresponds to the error term for the utility	*-5.48*
ASC_{HSR}	Alternative Specific constant for air that corresponds to the error term for the utility	*-0.8*
β	Sensitivity of passengers to the safety level parameter	*1.5*
VoT_{air}	The value of travel time for air transport (€ per hour)	*€41.7*
VoT_{HSR}	The value of travel time for high-speed rail transport (€ per hour)	*€14.3*
VoT_{hyp}	The value of travel time for Hyperloop transport (€ per hour)	*€11.7*
e_{air}	Carbon dioxide emissions of air transport (grams per passenger per km)	*90*
e_{HSR}	Carbon dioxide emissions of HSR transport (grams per passenger per km)	*40*
e_{hyp}	Carbon dioxide emissions of HSR transport (grams per passenger per km)	*0*
c_{hub}^{hyp}	Capital costs of a Hyperloop hub construction (million €)	*115.83*
c_{inf}^{hyp}	Capital costs of a Hyperloop infrastructure construction (million € per km)	*26.72*
$price^{hyp}$	Hyperloop ticket price (€ per km)	*0.1*
$Safety^{hyp}$	Safety Perception Index for Hyperloop	*1*
$Safety^{air}$	Safety Perception Index for air transport	*1*
$Safety^{HSR}$	Safety Perception Index for HSR	*2*
$Budget$	Total Budget Available for Hyperloop Network (Million €)	*200000*

Table 6.1: The parameter values set-up for the baseline experiment experiment.

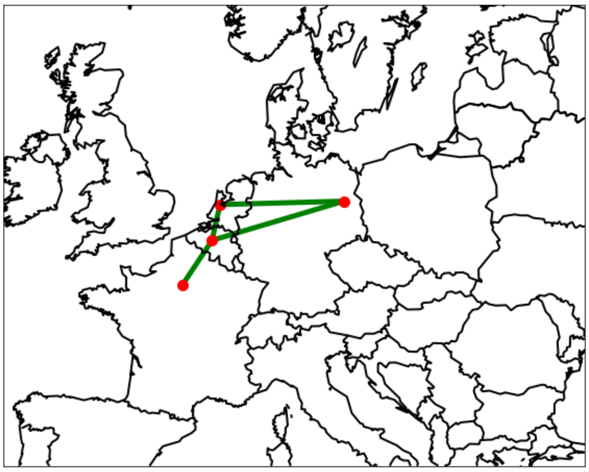

Figure 6.1: The generated network for the Utility Maximization Objective in baseline experiment.

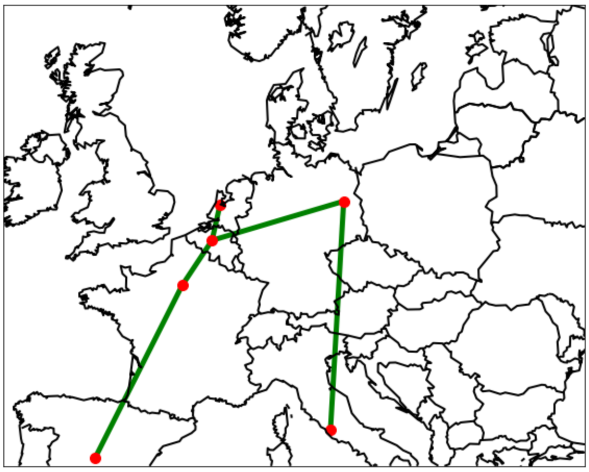

Figure 6.2: The generated network for the Probability of Purchase Maximization Objective in baseline experiment.

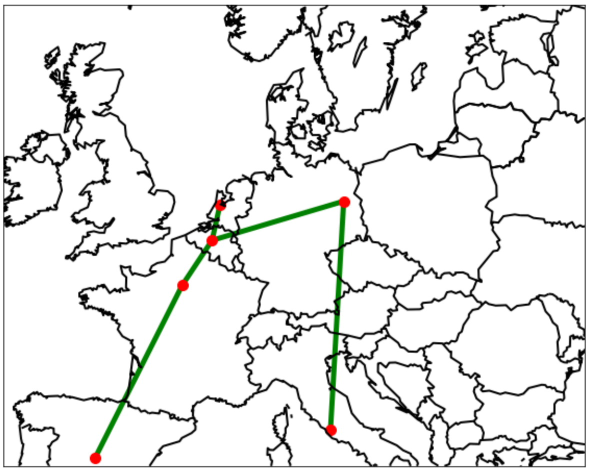

Figure 6.3: The generated network for the Emission Minimization Objective in baseline experiment.

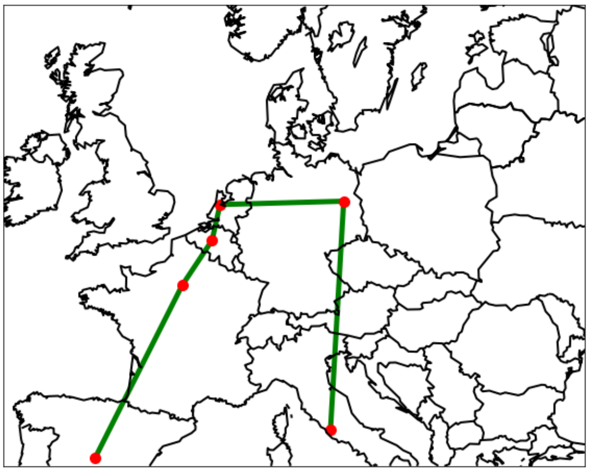

Figure 6.4: The generated network for the Revenue Maximization Objective in baseline experiment.

KPIs	Unit	Utility Maximization (Figure 6.1)	Probability Maximization (Figure 6.2)	Emission Minimization (Figure 6.3)	Revenue Maximization (Figure 6.4)
Number of Hubs	-	4	6	6	6
Number of Routes	-	4	5	5	5
Total Capital Cost	*Million €*	85201.616	186488.316	186488.316	186488.316
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	249.62	14731.844	14731.844	14731.844
Years to Break Even	-	Infesiable	14	14	14
Total Generated Emissions	*Tons*	19052.921	9224.071	9224.071	9224.071
Modal Share of Hyperloop	*%*	8.89	39	39	39

Table 6.2: The Key Performance Indicators of the model output with the baseline experiment

The resulting Hyperloop network decisions have been visualized for each of the objective functions identified and formulated previously in this report. An overview of the key performance indicators of the simulated Hyperloop network can be found in Table 6.1. The resulting network visualization for the objective function of **Utility Maximization** can be found in Figure 6.1. The simulated network results in the construction of four Hyperloop hubs in Amsterdam, Brussels, Berlin, and Paris. Locations Rome and Madrid have not been selected as Hyperloop hubs in this simulation. Interestingly, the average modal share of Hyperloop across all possible trips is only 8.89% which reflects a low utilization rate. The modal share of Hyperloop is further reflected in the feasibility of the entire system as the system is unable to make profits. Compared to the other objectives, it can be observed that the total emissions generated by the number of trips completed are substantially higher. This can be attributed to the low usage percentage of Hyperloop as the alternative transport modes emit higher volumes of carbon dioxide.

The simulated network visualization for the **Probability of Purchase maximization** objective can be found in Figure 6.2. This simulated network consists of a hub at all selected nodes. The resulting Hyperloop network has higher capital costs as the number of hubs to be constructed increases from the first objective. Contrastingly, the created network is able to make a profit each year and is expected to break even within 14 years of operation. Perhaps the most striking output is the modal share of Hyperloop, which has been predicted as 39%.

The Emission Minimization objective results in an identical Hyperloop network compared to the probability of purchase maximization objective output. As such, the key performance indicators for the generated Hyperloop network are also identical to one another. The simulated network for **the revenue maximization** objective has a slightly different network structure. The Hyperloop hub constructed in

Berlin is directly connected with infrastructure to the Hyperloop hub in Brussels, compared to the Amsterdam hub in the emission minimization objective output. The modal share of Hyperloop amongst the alternatives remains at 39% in both scenarios. The visualized network for the emission minimization objective and the revenue maximization objective can be found in Figures 6.3 and 6.4, respectively. The striking revelation of the baseline experiment is that apart from the Utility Maximization scenario, the remaining three objective functions result in more or less the same network structure with the exception of a single line. It seems that in order to maximize revenue, minimize emissions, and maximize the probability of usage, all possible locations need to have a Hyperloop hub. The price level set for the baseline seems to offset the increasing costs of constructing more hubs with the increased usage of Hyperloop. The sensitivity of the model to the ticket price will be explored further in the Ticket Price Experiment.

The available budget has been identified as a critical constraint for the network structure. This constraint reflects the realism of infrastructure costs for mega-projects such as a prospective Hyperloop network and its components. Therefore, an analysis was conducted to observe the behavior of the model with respect to the changing budget available. The graph depicting this behavior can be seen in Figure 6.5. It can be observed that at least a budget of €10 billion is necessary to construct an operational line of Hyperloop. The fluctuations in the number of hubs are related to the ability to connect further nodes such as Spain and Italy. Specifically, the decreases in the number of hubs and the number of routes are related to connecting longer distances at the expanse of shorter distances. One such example can be seen in Figure 6.6, where the number of hubs decreases from 3 to 2 whilst the number of route are reduced to 1 compared to 2. The main takeaway from this analysis is that at least a budget of 190 billion € is necessary to be able to construct a hub at every possible location. It has been also observed that the model tends to gravitate towards Minimum-Spanning Trees for a network with budget constraints.

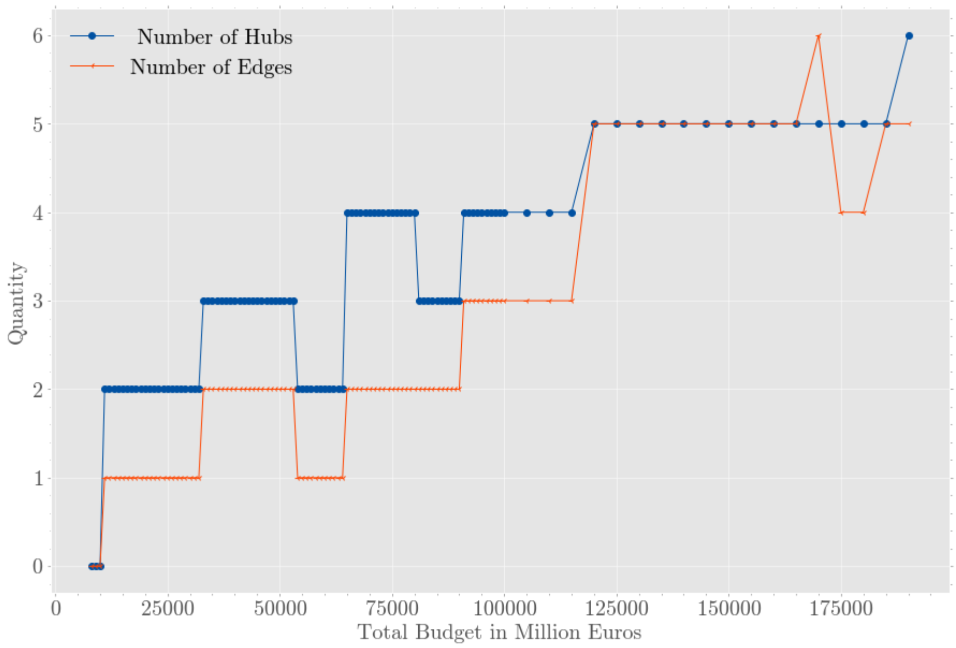

Figure 6.5: Number of hubs and nodes constructed with the available budget.

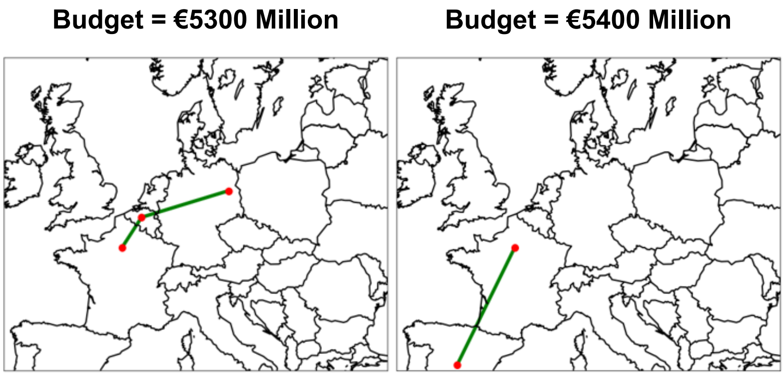

Figure 6.6: The behaviour of the model showcasing a decrease in number of nodes and lines despite an increase in the available budget.

The formulation of the model enables the decision to construct an entire network simultaneously. However, infrastructure networks have often grown over time. The European Union has identified this trend as set several milestones where the investment toward infrastructure is expected to increase in alignment with the connectivity of the regions [31, 32]. In order to gain insights toward an incremental expansion of the Hyperloop network within the region, the simulation was run to replicate this policy direction. Each discrete time step will represent a wave of investment toward the Hyperloop network. Therefore, the simulation was set-up to have discrete iterations where a new decision toward line planning will be made and the previous decision cannot be undone. The resulting network for each discrete time step can be found in Figure 6.7. The model behaves in a way that aims to use the budget as efficiently as possible by enabling travel with Hyperloop between the nodes with as little infrastructure investment as possible. Hence, the initial decision is to connect Amsterdam and Brussels which are the two closes nodes amongst all the candidates nodes.

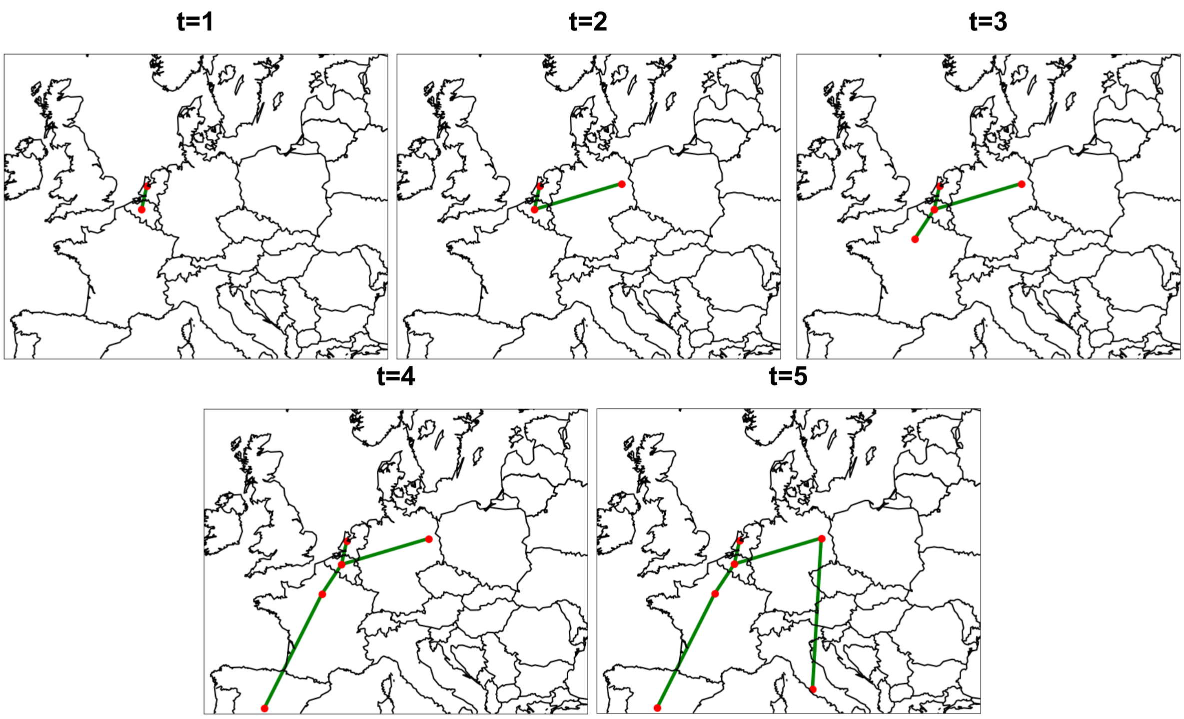

Figure 6.7: The Iterative Process of Hyperloop network expansion over discrete time periods with fixed investments.

6.2. Ticket Price Experiments

The travel costs per passenger represent a critical decision for the operating company. There are significant trade-offs included with different pricing strategies. Lower ticket prices might make Hyperloop more attractive to the public and therefore result in a higher modal share for Hyperloop. On the other hand, this might lead to small margins of profit if any for the operating company and might not be desirable. Nevertheless, European Commission or national authorities might desire lower prices to curb the negative externalities of competing travel modes. The involvement of multiple stakeholders with varying objectives makes the pricing strategy a complex issue. In order to be able to observe the effects of ticket prices on the key performance indicators of the Hyperloop network, ticket price experiments were designed.

The values of the parameters used in this experiment are identical to those utilized in the baseline experiment as outlined in Table 6.1. The only exception lies in the value of $price^{hyp}$ which will have three different values for each scenario designed. The first of the scenarios, T1, represents the ticket price suggested by Elon Musk in the initial design. In "Hyperloop Alpha", the suggested ticket price for a trip in California was roughly €0.05 per kilometer per passenger. Scenario T1 replicates this suggestive price by setting the value of $price^{hyp}$ to €0.05. Scenario T2 and Scenario T3 have been created for the purposes of this case study. In both scenarios, the ticket price for Hyperloop per passenger per kilometer has been doubled. Therefore, the value of $price^{hyp}$ will be set as €0.1 for Scenario T2 and as €0.2 for Scenario T3. The output of the model for each scenario will be discussed in the following subsections 6.2.1 and 6.2.2. The output of Scenario T2 is identical to the baseline experiment as the parameter values have been replicated. Therefore, the results of Scenario T2 will not be discussed further, and the related output can be in Section 6.1.

6.2.1. Scenario T1

In Scenario T1, the ticket price of Hyperloop per passenger per kilometer has been reduced to €0.05. The low costs are an attempt to capture more demand from the passengers. Due to the formulation of the utility function, the travel costs have a direct impact on the probability of usage. The outputted network design for the different objective functions of the model can be found in Figures 6.18,6.19,6.20, and 6.21. The key performance indicators of the output can be found in Table 6.5. Interestingly, similar to the baseline experiment, the generated networks for the objectives of probability maximization, emission minimization, and revenue maximization are similar to each other. The model behaves in a way to connect all nodes to the main network in order to make Hyperloop an alternative for all trips. For some travel itineraries that are not directly connected with infrastructure, this would mean an undesirable trip. For instance, traveling from Rome to Madrid requires 4 transfers at various stations. Passengers would receive low utility for choosing Hyperloop for such a trip. Contrarily, the utility maximization objective results in a lower number of hubs selected but direct links between all selected nodes. The generated network aims to ensure all origin destinations are connected directly to counteract the negative impacts of having multi-legged indirect trips where layovers are necessary.

Comparing the key performance indicators with the baseline experiment, one can observe that lower travel costs have had several consequences for the system. First, for the objective function of utility maximization, the annual revenue to be made from a Hyperloop system has increased substantially from €249 million to €611 million. Despite lower revenue per passenger, the increase in the number of passengers using the system has managed to offset the loss in revenue. The modal share of Hyperloop increases from 8% to 15% in this objective. The opposite is true for the remaining three objective functions. The annual revenue of the system decreases from €14731 million to €11460 million in Scenario T1, where the increase in modal share fails to sufficiently balance the loss in revenue per person.

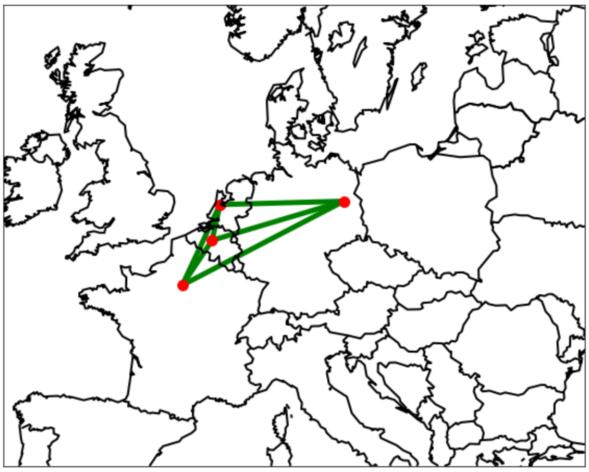

Figure 6.8: The generated network for the Utility Maximization Objective in Scenario T1.

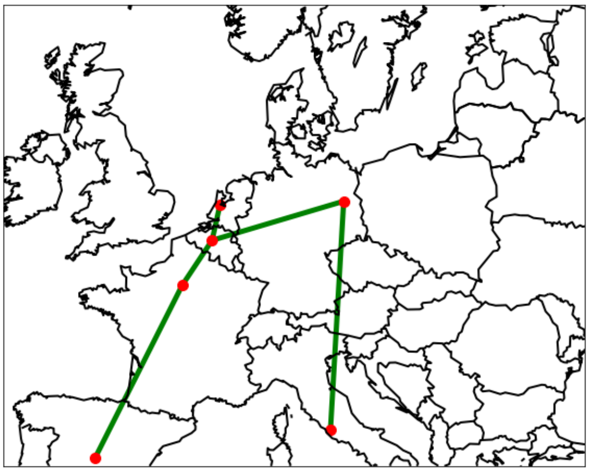

Figure 6.9: The generated network for the Probability of Purchase Maximization Objective in Scenario T1.

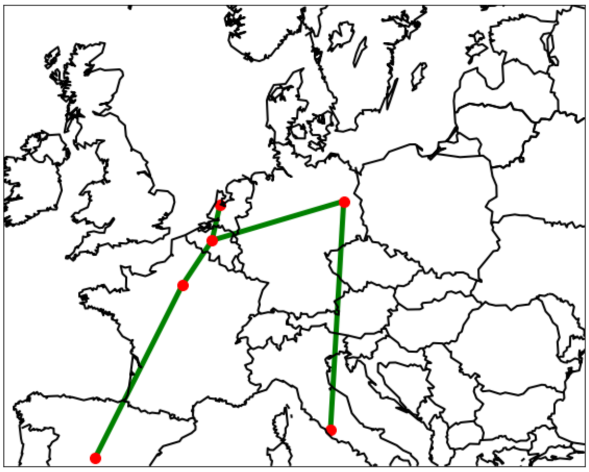

Figure 6.10: The generated network for the Emission Minimization Objective in Scenario T1.

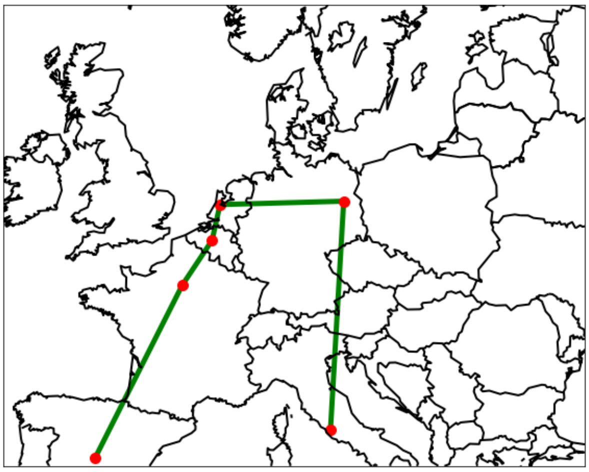

Figure 6.11: The generated network for the Revenue Maximization Objective in Scenario T1.

KPIs	**Unit**	**Utility Maximization (Figure 6.7)**	**Probability Maximization (Figure 6.8)**	**Emission Minimization (Figure 6.9)**	**Revenue Maximization (Figure 6.10)**
Number of Hubs	-	4	6	6	6
Number of Routes	-	6	5	5	5
Total Capital Cost	*Million €*	185989.456	186488.316	186488.316	190771.171
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	611.307	11460.283	11460.283	11460.283
Years to Break Even	-	5993	18	18	19
Total Generated Emissions	*Tons*	18394.246	4456.103	4456.103	4456.103
Modal Share of Hyperloop	*%*	15.98	58.55	58.55	58.55

Table 6.3: The Key Performance Indicators of the model output with Scenario T1.

6.2.2. Scenario T3

Scenario T3 represents the assumption that the ticket prices per passenger per kilometer increase to €0.2 compared to €0.1 from the baseline experiment. The resultant networks for all objectives can be found in Figures 6.12,6.13,6.14, and 6.15. Similar to previous scenarios, one can observe that the generated networks for the objectives of probability maximization, emission minimization, and revenue maximization are identical. Interestingly, the higher price level results in a single line of Hyperloop between Amsterdam and Brussels in the utility maximization objective. This phenomenon could be attributed to the ticket prices being high enough that the utility of travel is negatively affected with newer routes available. The key performance indicators of the generated Hyperloop networks can be found in Table 6.4. An initial glance at the KPI values showcases that the modal share of Hyperloop decreases considerably compared to the baseline experiment as even the highest modal share is lower than 10%. Similarly, the annual revenue values for all four of the objectives have decreased compared to the baseline experiment, and the years needed for the system to break even have increased substantially. For the utility maximization objective, the system is not able to turn a profit in the first place. The emissions generated are considerably higher since the passenger prefer air and high-speed rail for their trips. Scenario T3 performs worse than the previous scenarios in every key performance category. This outcome will be further emphasized with the following subsection 6.2.3 where a trade-off analysis is conducted for the ticket price experiments.

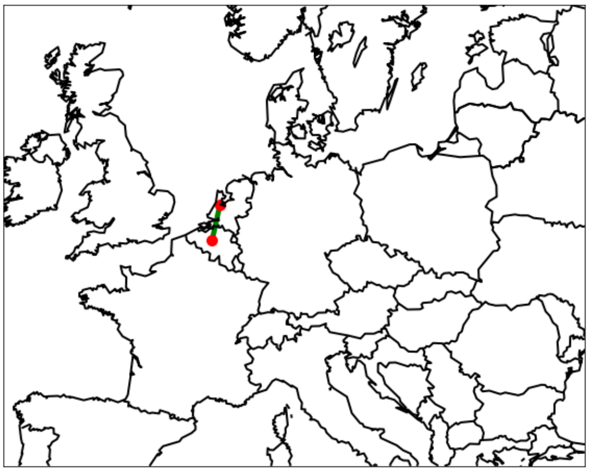

Figure 6.12: The generated network for the Utility Maximization Objective in Scenario T3.

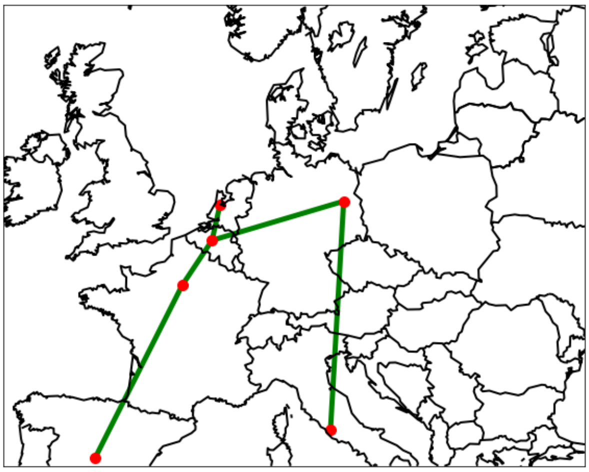

Figure 6.13: The generated network for the Probability of Purchase Maximization Objective in Scenario T3.

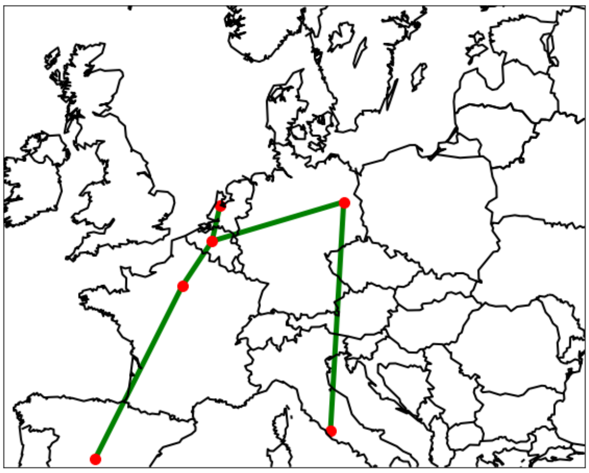

Figure 6.14: The generated network for the Emission Minimization Objective in Scenario T3.

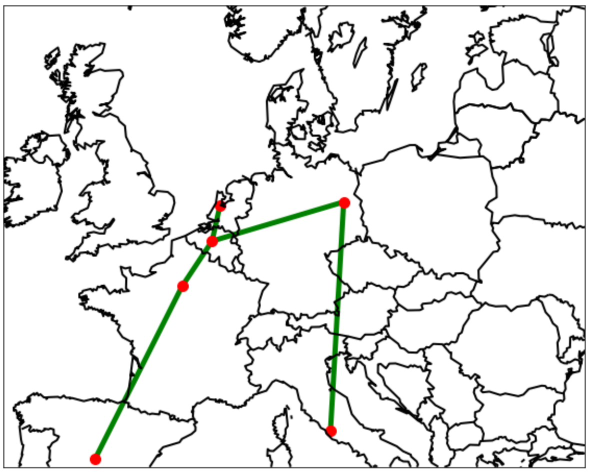

Figure 6.15: The generated network for the Revenue Maximization Objective in Scenario T3.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	2	6	6	6
Number of Routes	-	1	5	5	5
Total Capital Cost	*Million €*	10428.811	186488.316	186488.316	190771.171
Annual Operation Cost	*Million €*	5.170	867.072	867.072	867.072
Annual Revenue	*Million €*	289.024	3869.871	3869.871	3869.871
Years to Break Even	-	Infeasible	63	63	63
Total Generated Emissions	*Tons*	18854.055	17033.329	17033.329	17033.329
Modal Share of Hyperloop	*%*	1.23	9.79	9.79	9.79

Table 6.4: The Key Performance Indicators of the model output with Scenario T3.

6.2.3. Ticket Price Sensitivity

The simulation was set up to test the effects of the ticket price toward the modal share of Hyperloop within the market. The results were visualized in Figure 6.16. As expected, increasing the ticket price affects the modal share of Hyperloop negatively. This behavior is consistent with the formulation of the utility function. As Hyperloop becomes more expensive and all other parameters are left constant, more passengers decide to use air and high-speed rail modes. One of the critical thresholds for the passengers' behavior can be identified as €0.1 per kilometer per passenger. Setting the ticket price above this threshold results in the modal share of Hyperloop falling below 40%. Similarly, the price level of €0.2 per kilometer per passenger seems to be another threshold as passengers seem to become reluctant to use the system at this price level as the modal share falls below 10%. Finally, as the price level crosses the €0.3 per passenger per kilometer point, Hyperloop becomes irrelevant as an alternative.

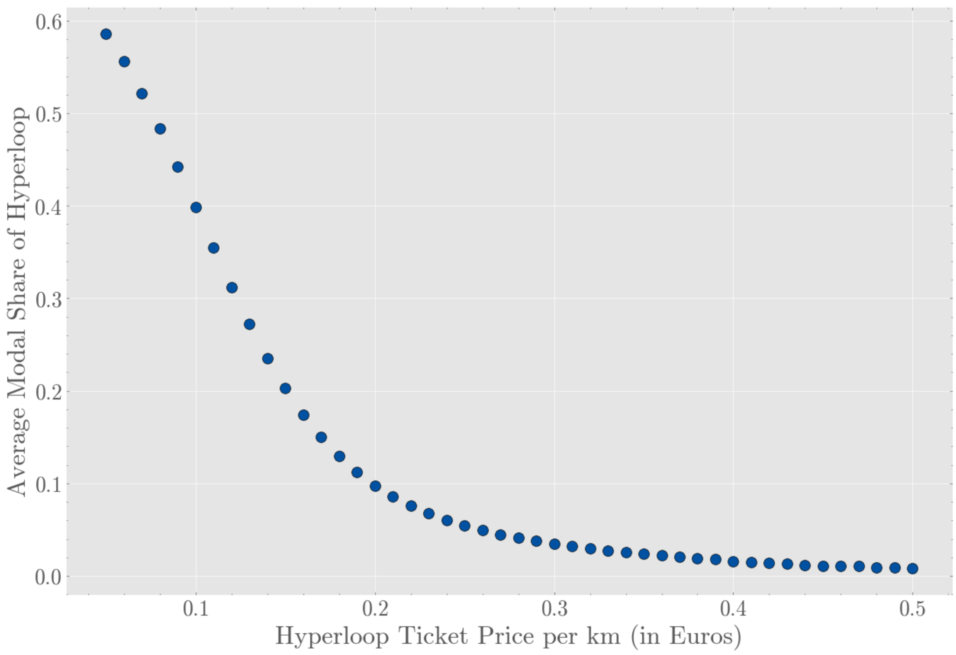

Figure 6.16: The Modal Share of Hyperloop compared to the ticket price set for Hyperloop.

The ticket price has significant effects on all of the key performance indicators. In order to have a better overview of the values of the key performance indicators through all of the scenarios and in order to gain insight into the efficiency of the scenarios, a Pareto frontier has been generated. The Pareto frontier was created to compare the KPIs of annual revenue and the modal share of Hyperloop achieved. The results can be seen in Figure 6.17. Scenario T1 represents lower annual revenue for the operating company whilst achieving a higher modal share of 58% for Hyperloop. On the other hand, Scenario T2 achieves higher annual revenues, sacrificing the modal share of Hyperloop to 39%. Scenario T3 seems to be dominated by the previous two scenarios where both the annual revenue and the modal share are lower. Scenario T3 is not a Pareto solution for the two KPIs considered. This outcome is consistent with the findings in 6.16 as the price level makes Hyperloop costly to use. Hence, the generated Hyperloop network in this scenario fails to entice the passengers.

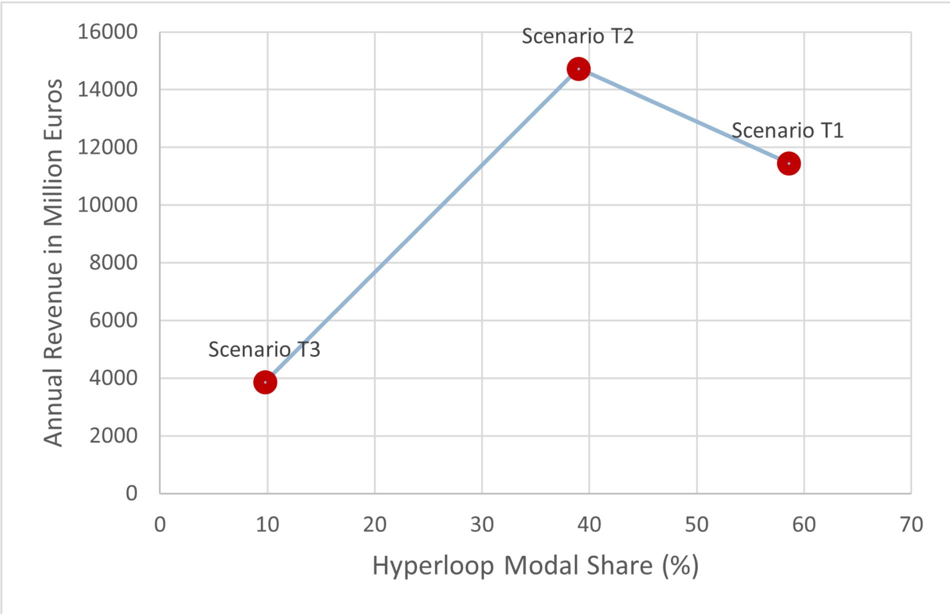

Figure 6.17: The Pareto frontier of Scenarios T1,T2,T3 with respect to annual revenue and modal share.

6.3. Safety Perception Experiments

Safety perception of the passengers toward the Hyperloop technology affects the choice passengers make on their decisions. This has been revealed as true by the stated preference surveys conducted concerning the Hyperloop technology by several studies. Abouelela et al. pinpoint it as one of the most important factors besides travel time and travel costs [2]. Therefore, the technological improvements toward making the design safer for passengers will impact the Hyperloop network usage and the adoption of the technology. The safety perception experiments were designed to test the consequences of varying levels of safety perception of Hyperloop. Safety is a concept that is hard to quantify for a novel technology. In order to circumnavigate this issue, an index-based approach was adopted. The index of safety will be compared to the safety perception index of competing transport modes. All of the parameters used in the model are identical to the parameters defined for the baseline experiment. The overview of the parameters can be found in Table 6.1. The value of the parameter $Safety^{hyp}$ is the only independent variable in the design of the experiment for the safety perception. In Scenario S1, the value of $Safety^{hyp}$ will be set to 0.5, meaning that the mode is perceived as more dangerous than air transport. Similarly, in Scenario S3 the value of the parameter $Safety^{hyp}$ will be set to 2. This means that in Scenario S3, Hyperloop is viewed as safer than air transport and as safe as High-Speed Rail by the public. Scenario S2 is identical to the baseline experiment and thus, the output will not be discussed to avoid redundancy.

6.3.1. Scenario S1

Scenario S1 lowers the safety perception level to 0.5 compared to 1 in the baseline experiment. The generated networks from the simulation have been visualized in Figures 6.18, 6.19,6.20, and 6.21. The pattern from the previous scenarios is replicated where the utility maximization objective has a different network structure than the remaining four objective function solutions. The key performance indicators related to the outputted networks can be found in Table 6.5. Utility maximization objective results in only a single line being opened between Amsterdam and Brussels. The modal share drops significantly to 0.9% among the transport modes. Due to the low number of passengers, the annual revenue falls to the level of €289.024 million. The emissions of the total system are one of the highest among all of the scenarios where 19210 tons of carbon dioxide is emitted annually. In the remaining objective function results, the modal share has seem to have fallen from 39% to 26%. Therefore, the annual revenue decreases for all of the objective functions compared to the baseline experiment.

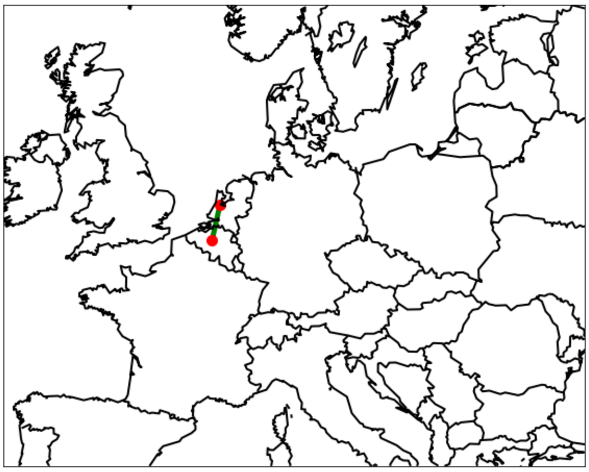

Figure 6.18: The generated network for the Utility Maximization Objective in Scenario S1.

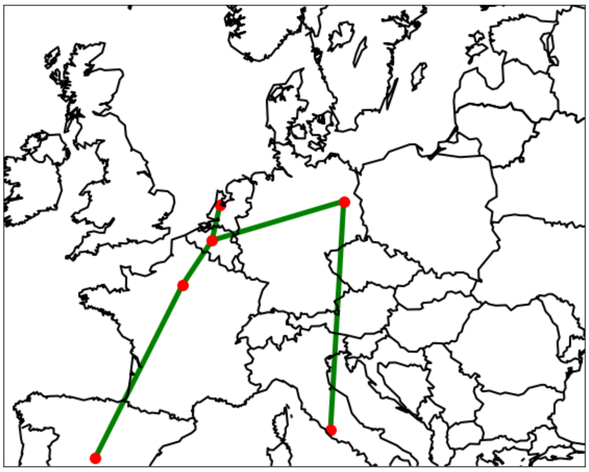

Figure 6.19: The generated network for the Probability of Purchase Maximization Objective in Scenario S1.

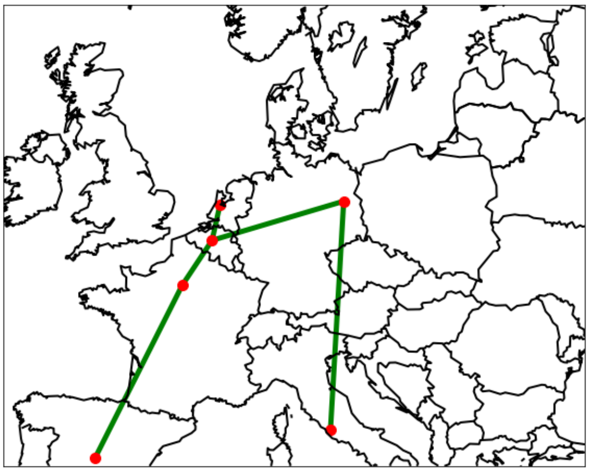

Figure 6.20: The generated network for the Emission Minimization Objective in Scenario S1.

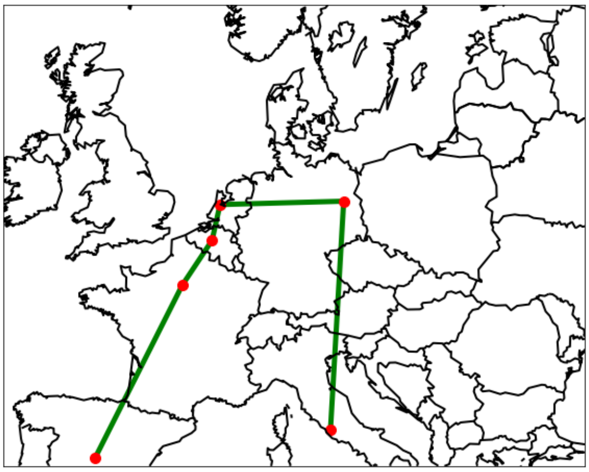

Figure 6.21: The generated network for the Revenue Maximization Objective in Scenario S1.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	2	6	6	6
Number of Routes	-	1	5	5	5
Total Capital Cost	*Million €*	10428.811	186488.316	186488.316	190771.171
Annual Operation Cost	*Million €*	5.170	867.072	867.072	867.072
Annual Revenue	*Million €*	289.024	10226.927	10226.927	10226.927
Years to Break Even	-	Infeasible	20	20	21
Total Generated Emissions	*Tons*	19210.206	11961.433	11961.433	11961.433
Modal Share of Hyperloop	*%*	0.9	26.53	26.53	26.53

Table 6.5: The Key Performance Indicators of the model output with Scenario S1.

6.3.2. Scenario S3

Scenario S3 assumes that technological developments increase the safety perception of the Hyperloop. The safety perception index has been increased to 2 in this scenario. Compared to a lower safety perception index in the baseline experiment of 1, the safety perception is assumed to be higher than the safety perception of air transport and on par with the safety perception of High-Speed rail. The results of the simulations for all four of the objective functions can be found in Figures C.13, C.14,C.15, and C.16, respectively. The generated networks are similar to the generated networks in Scenario T1. This further solidifies the behavior of the model in experiments where the utility received from the Hyperloop is increased. In the first objective of utility maximization, the model behaves in a way to provide direct connections to the selected hubs, whilst in the remaining three objectives a minimum spanning tree is created. The key performance indicators of the experiment for all of the objective functions can be observed in Table 6.6. The performance of the system is better than the baseline experiment as expected. An increase in safety results in the system performing better in all of the categories. The revenue for each scenario has increased whilst the emissions generated are lower. The modal share is affected positively and Hyperloop solidifies its share in the market. In the probability maximization, emission minimization and revenue maximization objectives Hyperloop is the most used transport mode with a modal share reaching 64%.

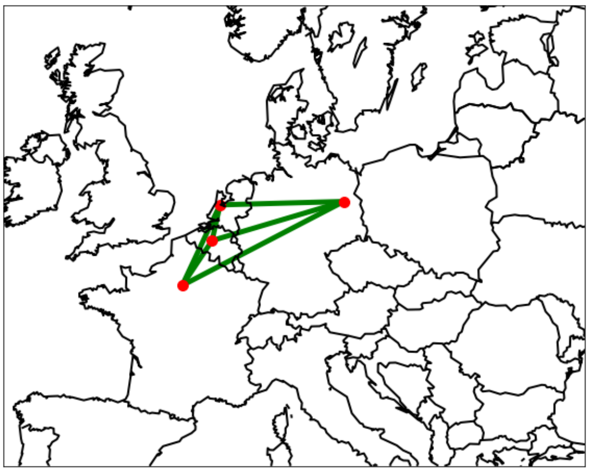

Figure 6.22: The generated network for the Utility Maximization Objective in Scenario S3.

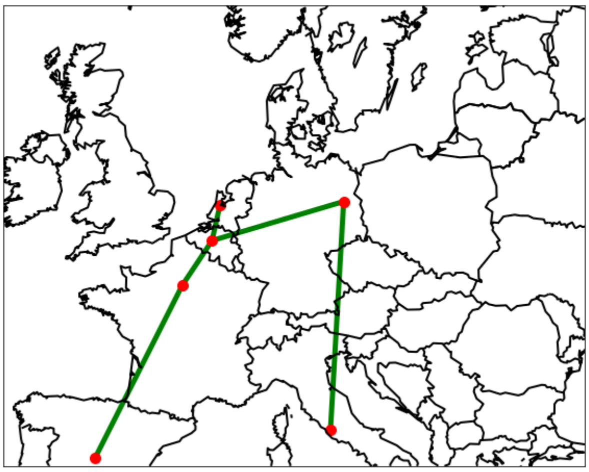

Figure 6.23: The generated network for the Probability of Purchase Maximization Objective in Scenario S3.

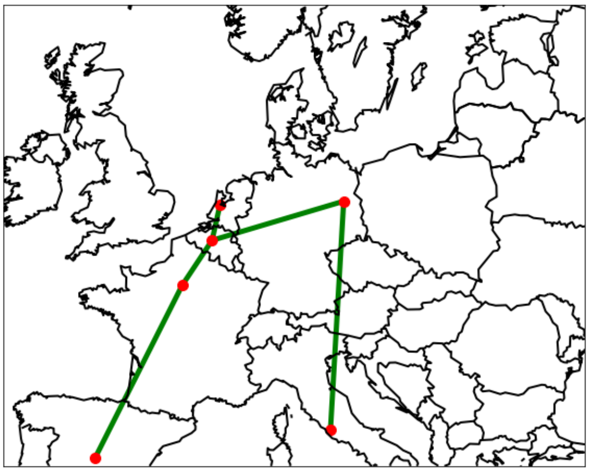

Figure 6.24: The generated network for the Emission Minimization Objective in Scenario S3.

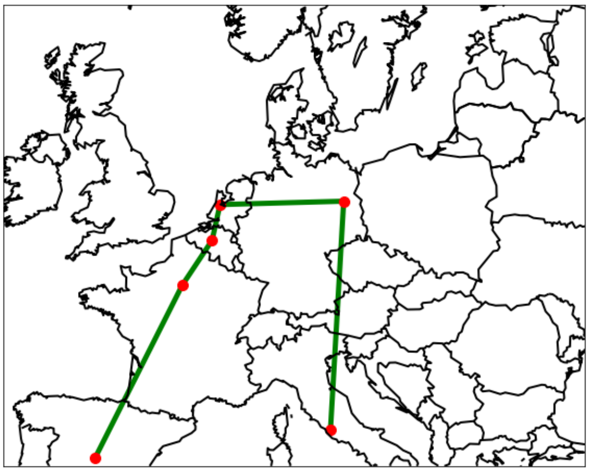

Figure 6.25: The generated network for the Revenue Maximization Objective in Scenario S3.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	4	6	6	6
Number of Routes	-	6	5	5	5
Total Capital Cost	*Million €*	185989.456	186488.316	186488.316	190771.171
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	1509.274	22482.823	22482.823	22487.823
Years to Break Even	-	200	9	9	9
Total Generated Emissions	*Tons*	18324.807	4660.8669	4660.8669	4660.8669
Modal Share of Hyperloop	*%*	22.41	64.53	64.53	64.53

Table 6.6: The Key Performance Indicators of the model output with Scenario S3.

6.3.3. Safety Perception Sensitivity

Safety has been determined to have a direct impact on the Hyperloop adoption rate and indirectly influence the key performance indicators of the system. In order further identify the relationship between safety and the key performance indicators of emissions and the annual profit of the system, a sensitivity analysis was conducted. The value of safety was increased incrementally from the lowest safety perception index of 0.1 to the maximum safety perception index value of 3. The maximum value would reflect a public perception that Hyperloop is perceived to be safer than both air transport and High-Speed Rail. The model was run with the utility maximization objective and the price level was kept constant. The findings have been visualized in Figures 6.26 and 6.27. The critical insight to be had from this analysis is that the safety perception value of 1 is an important threshold for the system. For safety perception index values lower than 1, the system performs considerably worse where the annual emissions are higher and the Hyperloop operating company fails to make a profit. On the other hand, for safety perception index values higher than 1, the annual emission of the system decreases 5%. Similarly, the Hyperloop is system is able to turn a profit for safety perception index values higher than 1. The findings of the sensitivity analysis suggest that it is paramount for Hyperloop to be perceived safer than air transport in order for the system to have desirable values of key performance indicators.

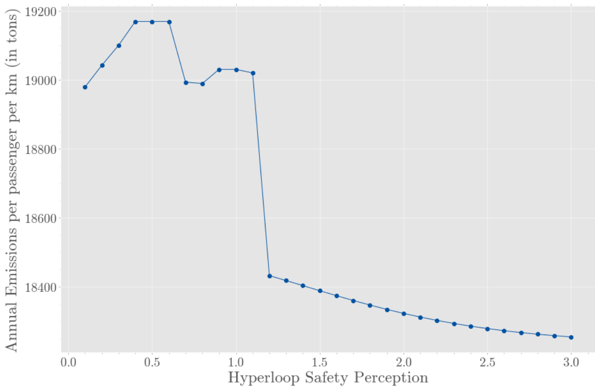

Figure 6.26: The relationship between the safety perception and annual emissions of the system for this experiment.

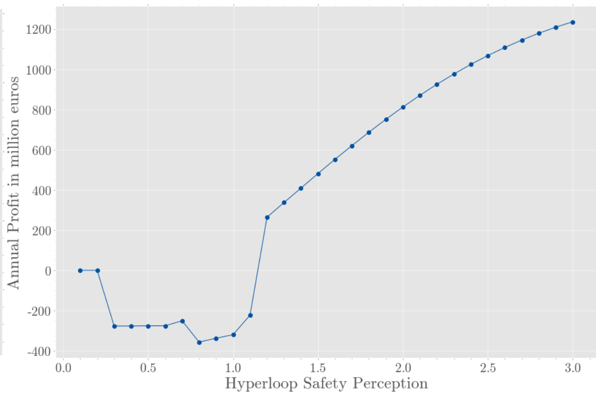

Figure 6.27: The relationship between the safety perception and annual profit of the Hyperloop system for this experiment.

6.4. Policy Intervention Experiments

This section is related to the experiments designed to assess the potential impacts of various policy interventions. Previously, in Chapters 1 and 5 the European initiatives towards incentivizing a modal shift towards more sustainable transport modes were discussed. It is likely that several policy interventions will supplement the realization of a Hyperloop network within the European Union. Scenario P1 assumes an extreme scenario where all short-haul flights are banned to curb the negative consequences of air transport such as carbon dioxide emissions. Such a policy could be considered if the improvements in mobility behavior seem unlikely to reduce the carbon footprint of passenger mobility. Scenario P2 is more mild compared to Scenario P1 where additional tax is imposed on all short-haul flights within Europe. These costs will completely pass on to the passenger via an increase in travel costs. Lastly, in Scenario P3 the total demand for Hyperloop will increase through the public perception of the technology as well as personal tastes gravitating toward Hyperloop further.

6.4.1. Scenario P1

Scenario P1 represents an extreme case within this case study. This scenario assumes that an EU-wide ban on short-haul flights has been put in place. The ban is assumed to have affected every trip with an airplane that could be performed with a rail-based mode under 4 hours. Due to the existence of Hyperloop in Europe, this results in a ban on all flights between the selected origin-destination pairs. Modified versions of the short*haul flight bans and/or plans to implement them already exist on a national level. For instance, France has banned national flight routes that can be replaced by 2.5-hour train trips. In Spain, there are plans to do the same until the year 2050 in order to reach carbon neutrality goals [111]. Therefore, in the distant future, short-haul flight bans could be prevalent. Scenario P1 exemplifies such a policy in the future where the passengers are unable to travel by air transport. Therefore, the choice model has been reduced to two alternatives, Hyperloop and High-Speed Rail. The assumption that High-Speed Rail trips are possible between all origin-destination pairs persists for this scenario. The output of the model and its network visualizations can be found in Figures 6.28, 6.29, 6.30 and 6.31. The network structure remains identical to the network structure generated in the baseline experiment. Nevertheless, the modal share of Hyperloop has increased substantially as expected. The performance of the network can be observed by the values of the key performance indicators in Table 6.7. The utility maximization objective has doubled in the modal share of Hyperloop and has reached 18% modal share. This value is still low as the network structure does not allow for trips with Hyperloop to and from Spain or Italy. The passengers are more likely to select High-Speed Rail to travel with lower costs at the expanse of travel times. On the other hand, in the remaining three objective function outputs, Hyperloop has become the most dominant transportation option. The modal share of Hyperloop has reached 71%. It seems that the passengers that are unable to travel to their desired destination via air have chosen to travel with Hyperloop. Therefore, a potential ban on short-haul flights greatly impacts the modal share of Hyperloop and could be a prime incentive toward a modal shift. This policy option could be an extreme alternative to curb emissions as the annual generated emissions have reached the lowest point among all of the scenarios considered in this study.

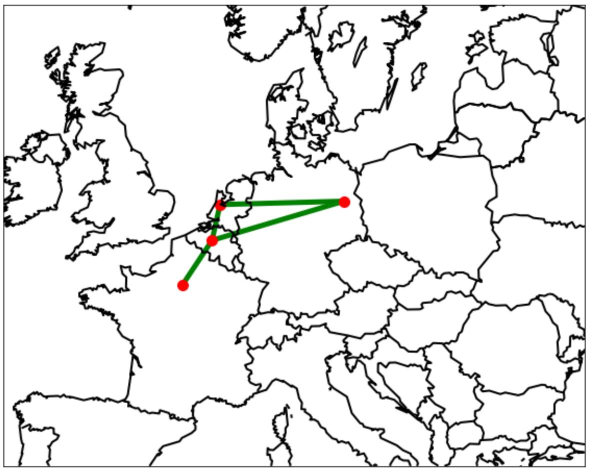

Figure 6.28: The generated network for the Utility Maximization Objective in Scenario P1.

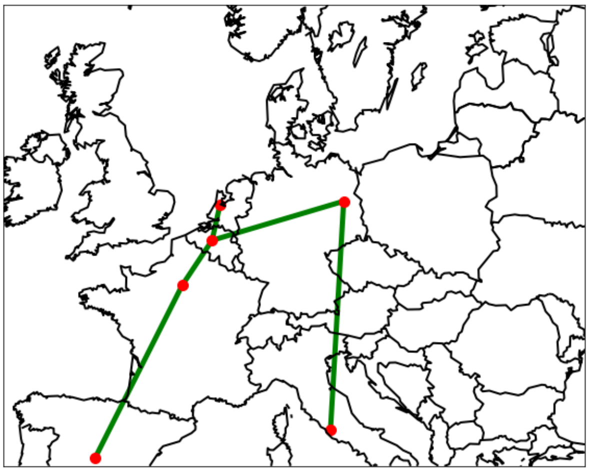

Figure 6.29: The generated network for the Probability of Purchase Maximization Objective in Scenario P1.

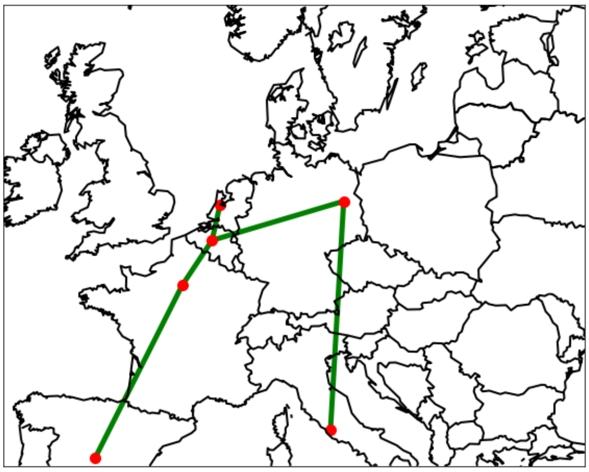

Figure 6.30: The generated network for the Emission Minimization Objective in Scenario P1.

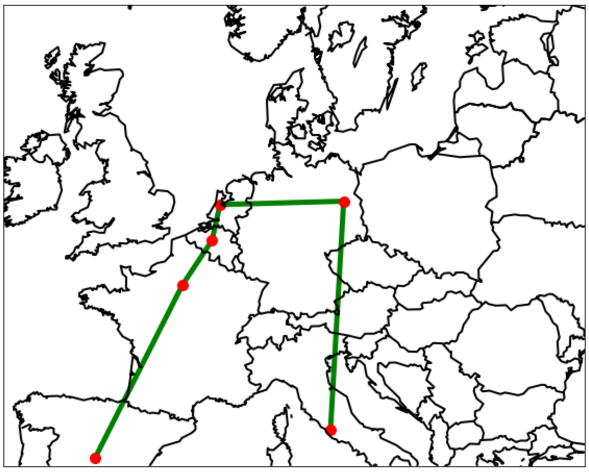

Figure 6.31: The generated network for the Revenue Maximization Objective in Scenario P1.

KPIs	**Unit**	**Utility Maximization (Figure 6.7)**	**Probability Maximization (Figure 6.8)**	**Emission Minimization (Figure 6.9)**	**Revenue Maximization (Figure 6.10)**
Number of Hubs	-	4	6	6	6
Number of Routes	-	4	5	5	5
Total Capital Cost	*Million €*	85201.616	186488.316	186488.316	186488.316
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	284.704	26145.875	26145.875	26145.875
Years to Break Even	-	Infeasible	8	8	8
Total Generated Emissions	*Tons*	3623.2071	2350.0695	2350.0695	2350.0695
Modal Share of Hyperloop	*%*	18.05	71.82	71.82	71.82

Table 6.7: The Key Performance Indicators of the model output with Scenario P1.

6.4.2. Scenario P2

Scenario P2 introduces an assumption that the European Union has decided to enforce an additional tax on short-haul flights within Europe. There are already taxes imposed on flights that vary on a national level. The increasing environmental pressure has pushed some national authorities to increase the taxes on trips made by airplane. For instance, the Netherlands has plans to increase flight passenger taxes substantially in 2023 [43]. This scenario follows a similar premise and incorporates a travel cost increase for all flights. This tax increase is reflected in the ticket prices fully. The experiment is run under the assumption that all flight travel costs double due to the new taxes incorporated and the remaining parameters are identical to the values used in the baseline experiment and outlined in 6.1. In reality, the taxes might vary from country to country even within the European Union. However, an aggregate assumption has been deemed sufficient to observe the effects of this potential policy on the Hyperloop network. The resulting network after the model has been run for all of the objectives can be found in Figures 6.32, 6.33,6.34 and 6.35. The generated networks are identical to the baseline experiment, implicating that the increased travel costs of air transport do not directly result in a change in the network structure. Nevertheless, there are significant differences in the key performance indicators of the network. The overview of the key performance indicators can be found in Table 6.8. For the objective function of utility maximization, the differences are observed to be minor. The annual revenue has increased slightly whilst the total generated emission has decreased. The main perpetrator for this positive change is the increase in the modal share of Hyperloop. In the baseline experiment, the modal share of Hyperloop was 8.89% while in this scenario it has increased to 9.51% for the utility maximisation objective. The increase in modal share is more dramatic when the model is run with the remaining three objective functions. The modal share has increased from 39% to 56% for all three of the objectives. This considerable increase has led to annual generated emissions being almost halved. The main takeaway from this experiment is that additional tax on the air transport costs for short-haul flights could facilitate a modal shift toward Hyperloop in a future where Hyperloop is mainstream.

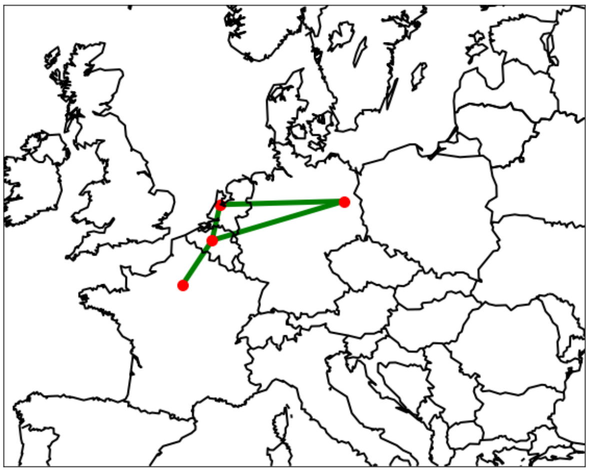

Figure 6.32: The generated network for the Utility Maximization Objective in Scenario P2.

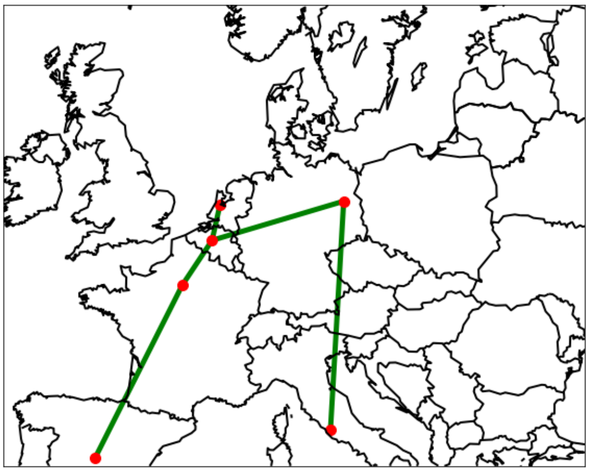

Figure 6.33: The generated network for the Probability of Purchase Maximization Objective in Scenario P2.

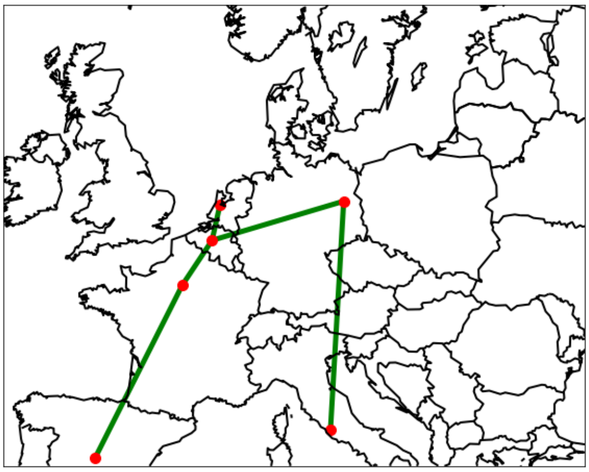

Figure 6.34: The generated network for the Emission Minimization Objective in Scenario P2.

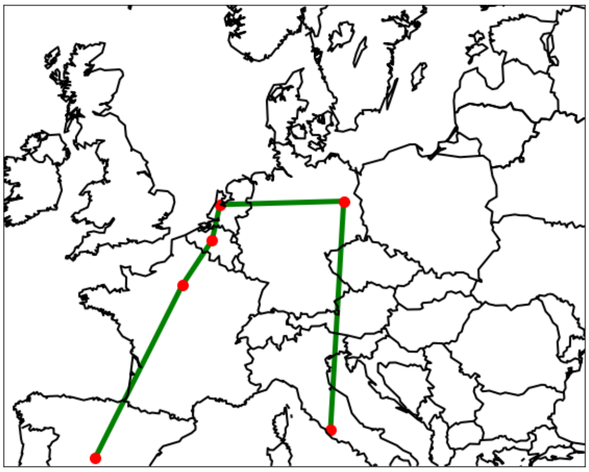

Figure 6.35: The generated network for the Revenue Maximization Objective in Scenario P2.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	4	6	6	6
Number of Routes	-	4	5	5	5
Total Capital Cost	*Million €*	85201.616	186488.316	186488.316	186488.316
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	273.791	22119.508	22119.508	22119.508
Years to Break Even	-	Infeasible	9	9	9
Total Generated Emissions	*Tons*	18799.788	4490.564	4490.564	4490.564
Modal Share of Hyperloop	*%*	9.51	56.11	56.11	56.11

Table 6.8: The Key Performance Indicators of the model output with Scenario P2.

6.4.3. Scenario P3

Scenario P3 represents a scenario in which the personal preferences for Hyperloop have shifted positively. Personal preferences and tastes result in a more positive perception of Hyperloop. The shift could occur to more awareness regarding the technology or positive developments in the Hyperloop technology. In order to represent this scenario, the unobserved attributes for the utility functions are used for each transport mode. In Chapter 3, the MNL model with the utility functions was introduced to be used in this study. Chapter 4 has described the explicit formulation of the utility functions where the unobserved part of the mode attributes are represented by the parameter ASC_{air} for the air transport and by ASC_{HSR} for the High-Speed rail transport. These values are based on previous choice model studies conducted in the literature. For the purposes of this experiment, the alternative specific constants for both air transport and high-speed rail have been reduced further by a factor of -1. ASC_{air} becomes -6.48, while ASC_{HSR} becomes -1.8. The resulting Hyperloop networks from the model output can be found in Figures 6.36, 6.37, 6.38, and 6.39. The network structure observed in all four objective functions is that there are not any deviations from the output structure in the baseline experiment except for a route choice for the revenue maximization objective. The single difference is the existence of a direct link between Berlin and Brussels instead of Berlin and Amsterdam. On the other hand, the key performance indicators highlight significant differences between Scenario P3 and the baseline experiment. The modal share can be observed to have increased in all four of the objectives. In probability maximization, emission minimization, and revenue maximization, the modal share of Hyperloop increases to 57.36% making Hyperloop the most commonly used transport mode. Similar to Scenario P2, the proposed changes in this scenario have also contributed to making Hyperloop a more attractive transportation alternative for passengers.

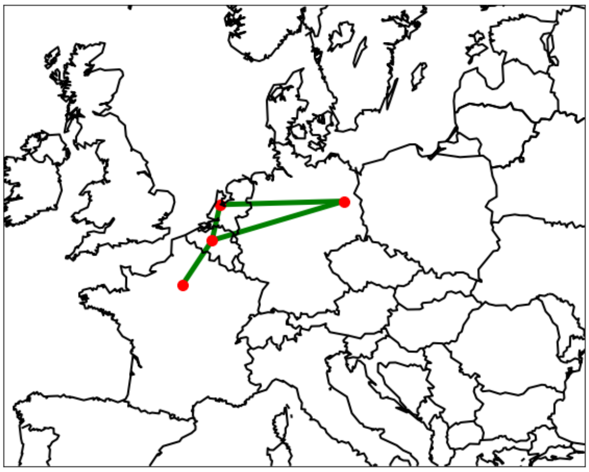

Figure 6.36: The generated network for the Utility Maximization Objective in Scenario P3.

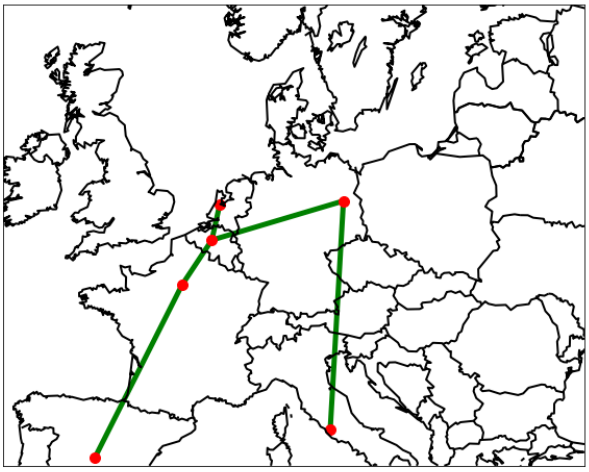

Figure 6.37: The generated network for the Probability of Purchase Maximization Objective in Scenario P3.

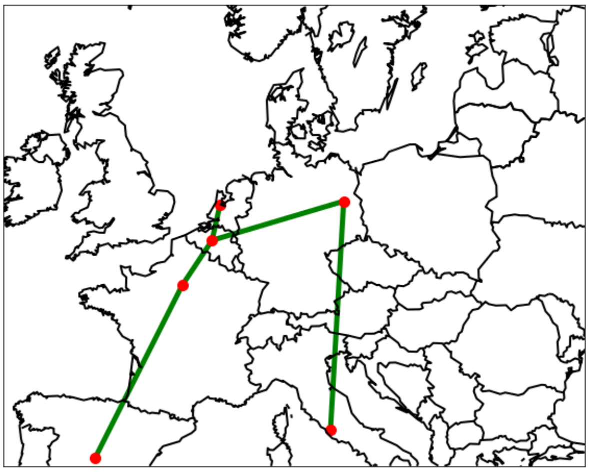

Figure 6.38: The generated network for the Emission Minimization Objective in Scenario P3.

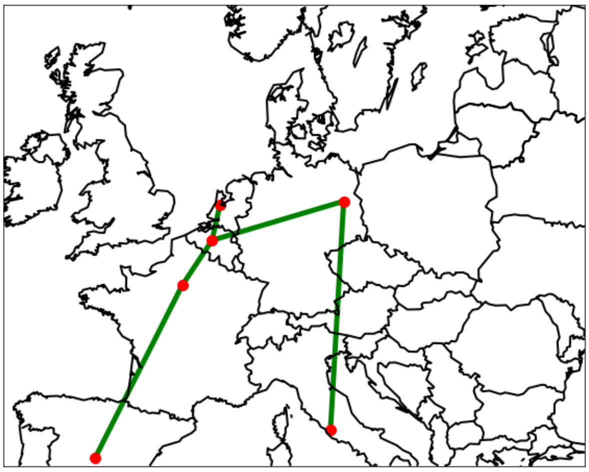

Figure 6.39: The generated network for the Revenue Maximization Objective in Scenario P3.

KPIs	**Unit**	**Utility Maximization (Figure 6.7)**	**Probability Maximization (Figure 6.8)**	**Emission Minimization (Figure 6.9)**	**Revenue Maximization (Figure 6.10)**
Number of Hubs	-	4	6	6	6
Number of Routes	-	4	5	5	5
Total Capital Cost	*Million €*	85201.616	186488.316	186488.316	186488.316
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	371.736	20320.088	20320.088	20320.088
Years to Break Even	-	Infeasible	10	10	10
Total Generated Emissions	*Tons*	19337.152	5914.945	5914.945	5914.945
Modal Share of Hyperloop	*%*	13.64	57.36	57.36	57.36

Table 6.9: The Key Performance Indicators of the model output with Scenario P3.

6.5. Overall Takeaways

The description of the scenarios, the generated networks in each scenario, and the detailed results of the key performance indicators for each scenario have been introduced in the previous sections of this Chapter. This section will summarize the overall takeaways by comparing the outcomes of the scenarios.

6.5.1. Objective Criteria

The network structure has been observed to be sensitive to the objectives rather than the scenarios. The model behaves in a way that the resources are utilized to make decisions that lead to a Minumum-Spanning Tree-like structure for probability maximization, emission minimization, and revenue maximization objectives. The model aims to open as many hubs as possible from the selected nodes for the case study. This behavior is expected as the inclusion of all nodes enables the Hyperloop to be an alternative for all travel itineraries. Thus, Hyperloop is available for passengers to be selected even if the utility of traveling with Hyperloop is relatively lower due to not having a direct connection between origin-destination pairs. Furthermore, all objective functions apart from the utility maximization objectives have similar outputs and the model behaves similarly to output identical structures as well as key performance indicators. The utility maximization objective makes the model behave differently. In this objective, the model decides to use the available resources to create a direct connection between selected nodes. This results in an extensive network where each origin-destination pair with a Hyperloop hub is connected directly. Even though the total utility passengers receive by traveling with Hyperloop is higher, the resulting networks perform poorly in key performance indicators such as emissions generated, the modal share of the Hyperloop, and the annual revenue. Hence, a trade-off exists where the volume of passengers traveling by Hyperloop is lower but those who choose to travel by Hyperloop receive higher utility.

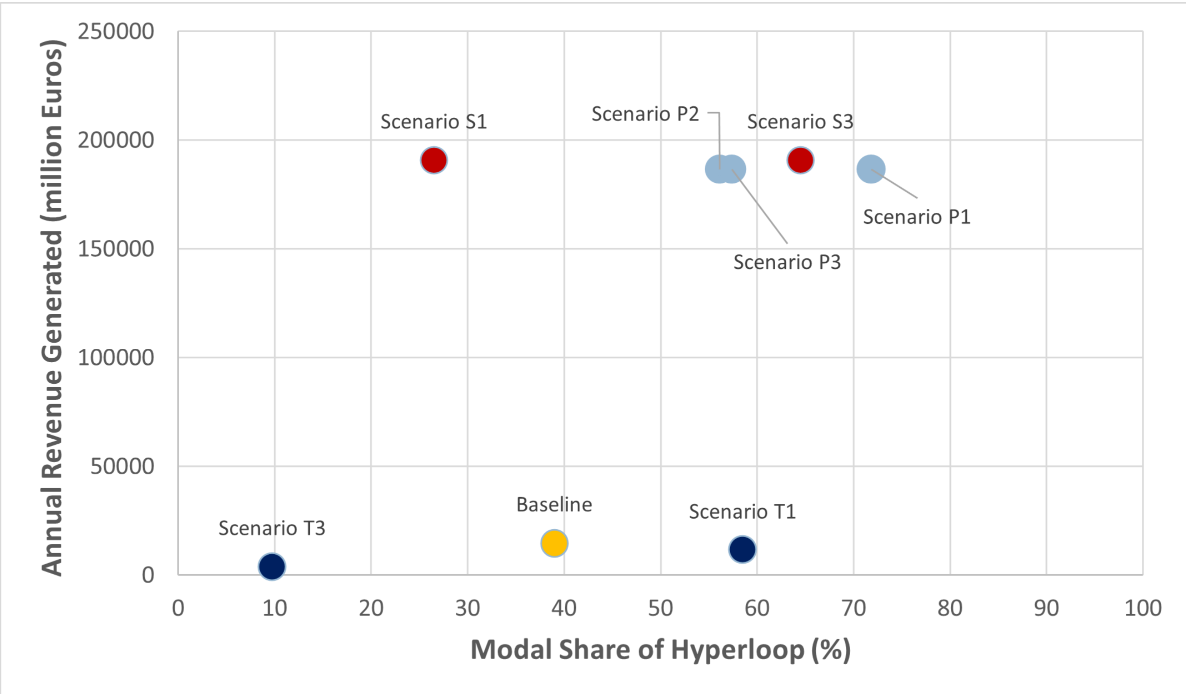

Figure 6.40: The Pareto Frontier of the KPIs Modal Share and Annual Revenue across all scenarios.

6.5.2. Effects of Ticket Prices

The impacts of a Hyperloop network in Europe have been further evaluated by testing several scenarios with various modifications made to the model. Three main categories of scenarios were designed. First, the ticket price per passenger per kilometer was changed incrementally to explore the sensitivity of the transportation network to Hyperloop travel costs. Second, the safety perception of Hyperloop was selected as a variable, and various perception levels were tested out in the model. Finally, several potential policy interventions that could complement the realization of a Hyperloop network in Europe were experimented with. The experiments were an attempt to assess the negative or positive impacts in the entire transportation sector with respect to the selected key performance indicators of the Hyperloop network. The Pareto Frontier depicting the performance of scenarios with respect to the annual revenues for the operating company and the modal share of Hyperloop can be found in Figure 6.40. The scenarios of ticket pricing seem to be relatively ineffective in having an impact on the annual revenue of the operating company. However, the changes in the pricing strategies are directly impactful on the modal share of Hyperloop. The trade-off between the number of passengers and the revenue per passenger seems to be key in this relationship. Furthermore, both Scenario T1 and Scenario T2 are dominated by other solutions of the model.

6.5.3. Importance of Safety Perception and Policy Impacts

The experiments conducted with the safety perception levels confirm previous studies in the literature, highlighting its importance in the modal share of Hyperloop in the market. The relatively lower perception of Hyperloop safety could result in Hyperloop losing modal share compared to the baseline experiment. On the other hand, a better safety perception than air transport could result in Hyperloop becoming the most attractive transport option as visualized also by Figure 6.26 and Figure 6.27. Hence, an efficient use of resources could be to strengthen the safety perception of the Hyperloop technology. The policy interventions are able to have a sizeable impact on the model output as there are deviations from the baseline experiment. Scenario P1 can be seen to be one of the most optimistic scenarios where the annual revenue is high and the modal share is above 70%. Scenarios P2 and P3 perform similarly in annual revenue but perform poorly compared to the modal share of Hyperloop in Scenario P1. Nevertheless, Scenario P2 and P3 perform similarly indicating that both of the policy options could supplement the realization of a Hyperloop network well by maximizing the positive impacts. Given the extreme nature of the policy intervention in Scenario P1, the other two policy interventions could be viable alternatives for policymakers.

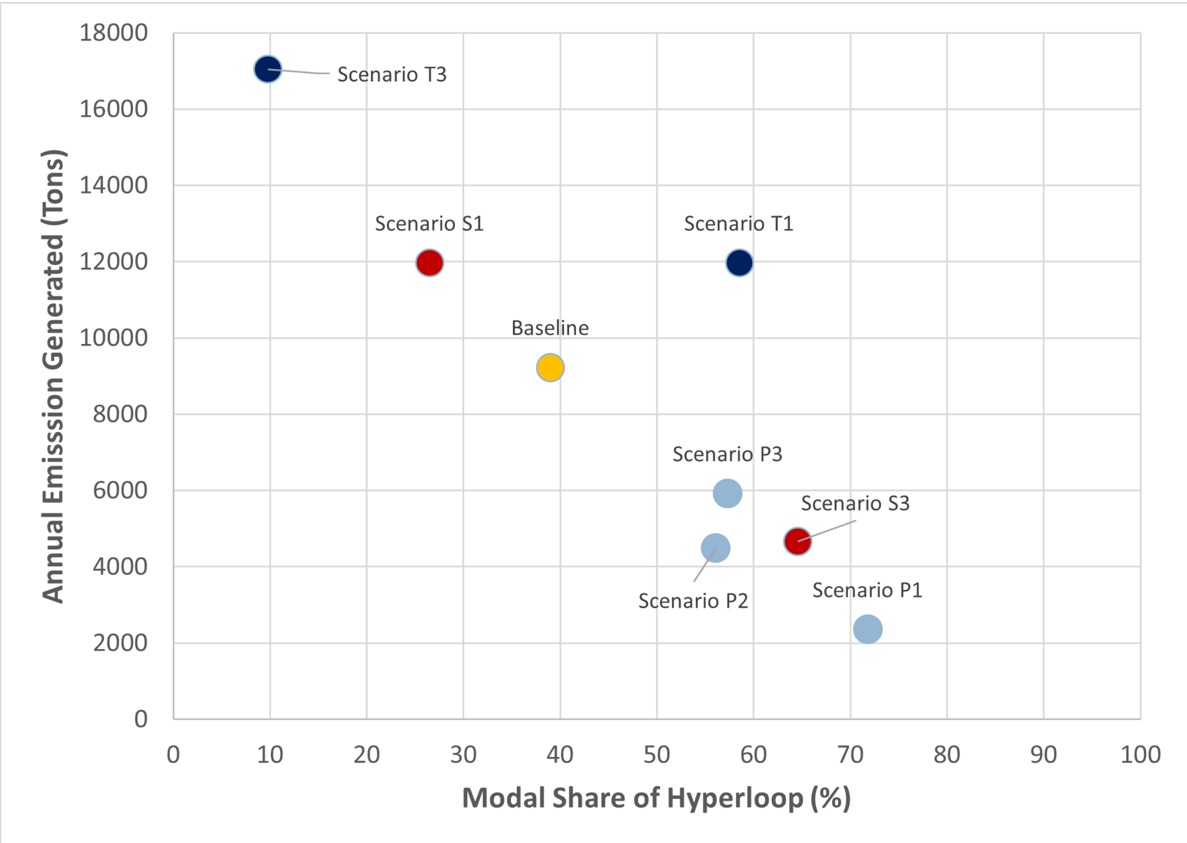

Figure 6.41: The Pareto Frontier of the KPIs Modal Share and Annual Generated Emissions across all scenarios.

6.5.4. Generated Emissions

One of the intended impacts of a Hyperloop network realization is to curb the emissions generated by passenger transport. To be able to observe the performances of the scenarios created for this study, a Pareto frontier depicting the relationship between the modal share of Hyperloop and the annual emissions was created. The visualization can be found in Figure 6.41. The ticket pricing strategies seem to be relatively ineffective compared to the other scenarios in reducing the annual emissions generated. Scenario T3 has the least desirable outcome as the annual emission generated are the highest. This further highlights that the travel costs of Hyperloop are critical in order to facilitate modal shift and high ticket prices will result in the system performing poorly. A similar conclusion can be reached regarding the safety perception. Scenario S1, where the safety perception index of Hyperloop was set to be lower than air transport, is also inferior in terms of the emissions generated KPI. Nevertheless, if the safety perception of Hyperloop could be improved to be higher than all other modes of transport, the annual generated emission are halved compared to the baseline experiment. All policy intervention scenarios have resulted in the annual generated emission being lowered substantially. Scenario P1 can be seen to be superior to other scenarios generated as the emission are lowest in this scenario. Scenario P2 and Scenario P3 also act as efficient policy interventions as the scenarios improve both of the KPIs. In terms of being more environmentally friendly, Scenario P2 performs slightly better. Thus, indicating that an additional tax on short-haul flights could be beneficial to create more incentives for Hyperloop usage.

7 Discussion & Conclusion

The Hyperloop technology possesses the potential to disrupt the global transportation sector, particularly in passenger transport, and could induce a significant shift in mobility patterns. However, the technology's novelty engenders skepticism regarding various design aspects of the Hyperloop system. The absence of fully operational testing facilities impedes conclusive determinations regarding the safety and efficiency of implementing Hyperloop. Given the intricate nature of public transport infrastructure networks and the uncertainties surrounding Hyperloop technology, in-depth research is imperative. Policymakers, investors, and innovators must meticulously evaluate the costs and benefits of Hyperloop technology prior to committing resources to establish a functional Hyperloop network. Failure to address these ambiguities may lead to alternative investments in policies aiming to establish a more sustainable transportation network. This study strives to bridge this knowledge gap by furnishing stakeholders with a decision-support tool to determine whether investing resources into an operational Hyperloop network adequately addresses the growing demand for passenger transport. The incorporation of multiple objective criteria in a facility-location network design problem serves two purposes. Firstly, it enables the identification and analysis of network design performance based on various performance indicators. Secondly, it facilitates the assessment of trade-offs between different network designs, elucidating the opportunity costs associated with implementing a proposed network. The formulated model can be further customized to encompass additional characteristics for specific regions or scenarios. While validating the model poses challenges due to the technology's novelty, this study corroborates the findings of limited existing research. Specifically, it reinforces the significance of safety perception in network design and network performance, aligning with the conclusions of a stated preference survey conducted by Abouelala et al. (2022) [2]. Furthermore, the designed experiments substantiate the findings of Agrawal et al. (2021) [4] that Hyperloop could potentially dominate the transportation market depending on travel time and costs. A reflection on the societal relevance of this study is discussed in Section 7.1 and the scientific relevance of this work is discussed in Section 7.2. Moreover, certain limitations persist within this study, which will be discussed in Section 7.3, followed by recommendations for further research in Section 7.4.

7.1. Societal Relevance

Societal relevance embodies the interconnection of scientific research with our communities, denoting the impact of research on public issues and policy-making [124]. This study endeavors to explore the prospective implementation of a Hyperloop network within Europe, encompassing a comprehensive array of social, environmental, and economic considerations intimately linked to the existing transportation systems. The assessment of societal impact in this research aligns with the three aforementioned categories [12].

7.1.1. Social Impacts

The present study formulates a facility-location network design model for the Hyperloop, serving as a decision support tool to aid stakeholders in the intricate decision-making processes concerning public transportation systems. Due to the socio-technical complexity inherent in public transport planning, policy decisions regarding investments in new transportation modes or the expansion of existing ones are challenging and of utmost significance. Hence, the ability to assess projected outcomes of transportation projects is a vital step to make well-informed decisions. The novelty of Hyperloop technology renders it lacking in both public users' comprehension and policymakers' understanding of its potential in facilitating a modal shift. This study's outcomes contribute to the comprehension of Hyperloop transport systems and inform the ongoing discourse on their technical and societal feasibility. Policymakers could use the results of this work as a first step toward exploring the role of Hyperloop networks to address transport challenges such as congestion, urbanization, and regional development. The experimental policies used in this study with auxiliary policies could serve as stepping stones toward the debate on new interventions. Furthermore, understanding the societal implications can lead to the formulation of appropriate policies, regulations, and incentives to support the technology's deployment while addressing potential concerns.

7.1.2. Environmental Impacts

The implementation of a Hyperloop network in Europe could facilitate the transition towards a more sustainable public transport system. The inclusion of the various objective criteria and the resulting network design allow for an analysis of trade-offs associated with respect to carbon emission contributions. Furthermore, a comprehensive analysis of the factors influencing passengers' decisions to opt for environmentally friendly transport modes can provide valuable insights for policymakers. These insights can aid in the formulation of additional incentives or investment decisions to reduce emissions from passenger transport activities. The examination of these contributing factors can lead to a deeper understanding of how to effectively allocate limited resources in future public transport planning, with the Hyperloop potentially playing a pivotal role in this transformative process. Policymakers can benefit from the findings of this study by conducting a thorough evaluation of the investment costs associated with Hyperloop systems in relation to their potential contribution to carbon emission reduction. The outcomes of this research can assist policymakers in assessing the viability of the Hyperloop technology as compared to alternative policies for achieving a more sustainable transportation system while ensuring seamless connectivity. By carefully weighing the environmental impact and cost considerations, policymakers can make well-informed decisions regarding the integration of Hyperloop systems into Europe's transportation infrastructure. Such informed decision-making is crucial for creating a greener and more efficient public transport system, aligning with the broader goals of sustainable development and environmental preservation.

7.1.3. Economic Impacts

This study can be valuable in terms of creating economic value for two distinct stakeholders interested in Hyperloop systems. First, the policymakers in the European Union member states may use the findings of this study to make more informed investment decisions in the public transportation sector. The results may be used to assess the economic risks associated with investing in Hyperloop and the opportunity costs involved with the substitute strategies to curb emissions and overcome the transport challenges within the region. The resulting network topologies with their capital cost and the performances of each network may be useful during the rolling out phase of the infrastructure if it is determined by the policymakers that the generated value of Hyperloop outweighs the costs. Further, the costs involved in different scenarios and the associated generated networks may contribute to the vital infrastructure decisions given that lock-in properties exist and tremendous investment is required. Second, Hyperloop developers may use the findings of this study to intensify their research and development efforts toward specific subsystems and components of Hyperloop. For instance, more resources could be allocated to the safety perception of Hyperloop which has proven to be critical for a modal shift toward Hyperloop. Thus, the work conducted in this study could lead to a decision-making process where the economic resources are utilized in a more efficient manner.

7.2. Scientific Relevance

The scientific relevance of this study can be found within the novel nature of the research undertaken. Notably, the Hyperloop technology constitutes a novel subject of inquiry, garnering attention relatively recently. As discussed in Chapter 1, the subject of Hyperloop network design has received limited research focus to date. In addressing this research gap, the present study employs a multi-objective optimization model to evaluate the resulting network design concerning various objectives. While multi-objective optimization models have been utilized historically to support strategic and tactical decision-making for other transport modes, such as High-Speed Rail and trains, this study represents a novel endeavor in the context of Hyperloop network design. To the best of the author's knowledge, no other study has considered multiple socio-economic objectives within the framework of Hyperloop network design. Consequently, this study constitutes a unique and innovative contribution to the field of Hyperloop research.

Furthermore, this study adopts the Multi-Nominal Logit (MNL) methodology to model the probabilistic mode choice behavior and the utility derived from selecting a specific travel mode for a given trip. The MNL methodology has gained widespread usage in transport planning research due to its efficacy in predicting passengers' mobility behavior based on a set of decision parameters. Often, a combination of stated preference surveys and revealed preference surveys is utilized alongside MNL models to anticipate modal shifts. However, this study stands out by integrating the Multi-Nominal Logit (MNL) methodology with a multi-objective optimization model, representing the first instance of such a combination within the realm of Hyperloop research. This approach contributes to advancing the understanding of transportation mode choice behavior, specifically in the context of Hyperloop technology.

7.3. Limitations

The methodology employed in this study encompasses several noteworthy limitations. Firstly, the adoption of a Multinomial Logit (MNL) model implies that the definition of the utility function plays a crucial role and directly impacts the choice model outcomes. The determinants influencing passenger choices vary across studies, and survey findings often yield contradictory results. This study considers travel time, travel cost, number of stops, and safety perception as defining factors, but other factors such as accessibility and comfort undoubtedly exert undeniable influence on public preferences. The inclusion of additional factors or adjustments to the utility functions could potentially yield different network designs and/or findings.

Secondly, the formulated model may encounter significant computational challenges as the number of candidate locations incorporated in the study increases. The requirement to consider all possible network design topologies while addressing multiple objective functions necessitates substantial computational resources. This limitation becomes particularly salient when dealing with larger-scale models, impeding the model's practical utility. Moreover, the model relies on assumptions that simplify real-world transportation systems and incorporates assumptions related to the technical specifications of the Hyperloop. Considering the various design concepts for Hyperloop technology and the absence of standardized technological parameters, the assumptions regarding the theoretical specifications of Hyperloop may become obsolete as the technology evolves and new design concepts emerge. Similarly, the operational and capital costs associated with Hyperloop are shrouded in ambiguity, with values derived from prior assumptions made in related studies. As testing facilities become more prevalent, the costs associated with Hyperloop may deviate from the assumptions made in this model. Consequently, even slight variations in these parameters could render the formulated model and its findings unrealistic.

The third limitation pertains to the case study conducted to test the formulated model. The model heavily relies on region-specific data to represent real-world conditions accurately. Consequently, selecting a different region for a case study could yield outcomes inconsistent with the findings of this study. Region-specific constraints such as geographical limitations or political and institutional uncertainties can significantly influence the design of a prospective Hyperloop network in different regions. Furthermore, expanding the scope of the case study may introduce computational challenges, while insufficient data may lead to misrepresentation of passenger behavior, thereby failing to encompass the full range of real-world possibilities.

7.4. Further Research

There are opportunities to expand and build on this study through further research. The first avenue of research lies in the expansion of the utility function considered in the Multi-Nominal Logit model. This study has considered four factors out of many attributes that affect the mode choices of the passengers out of simplicity and practicality. This results in the omission of factors such as comfort, accessibility, and frequency of available services that have effects on the mode choice decisions made by passengers. Expansion of the utility terms to include as many attributes of transport modes would be a better representation of the mobility behavior. Therefore, further research could focus on incorporating more attributes of passenger utility. Similarly, this study aims to capture to demand shift from air transport and rail-based modes to Hyperloop. In reality, it can be expected that a modal shift also occurs from other transport modes towards Hyperloop. Further research could identify the behavior of passengers when presented with a scenario of more transport modes being available to them. For instance, the potential consequences to the modal share of road transport are currently unknown in this study. The inclusion of more transport modes could dramatically change the performance of generated Hyperloop network designs and yield valuable insights.

The second avenue for future research lies in the formulation of the facility-location network design problem. This study has identified four objective functions that align with the transformative potential of Hyperloop. Subsequent investigations could enhance the formulated model by incorporating additional objective criteria. This expansion would contribute to a more comprehensive understanding of the intricate nature of transport infrastructure and facilitate an analysis of conflicting objectives within a prospective Hyperloop network design. Furthermore, the simplifying assumption made in this model regarding the decision-making process of realizing a Hyperloop network warrants further exploration. Specifically, the model assumes the absence of geographical obstacles in infrastructure construction between the selected nodes. Additionally, the chosen nodes in this study assume that the Hyperloop hubs will be situated in the geographical centers of the capital cities of the countries under examination. In reality, decisions regarding the available hub locations for Hyperloop networks may vary, and these hubs might be positioned in non-urban areas akin to airports. This assumption oversimplifies the considerations involved in multi-modality public transport decisions and the accessibility to Hyperloop services. Researchers can relax these assumptions to assess their impacts on Hyperloop network performance and offer insights into optimizing the utilization of limited resources.

This study has considered an analysis of the strategic level of Hyperloop network planning. The strategic level includes demand analysis and line planning operations. This results in the identification of an optimal facility location and the outputted network topology. The next phase of the planning includes tactical considerations such as timetable generation and rolling stock management. At the tactical level, resource allocation constitutes an important step in providing efficient service to passengers. The frequency of available trips and the capacities at different time intervals influence the decisions of passengers. In the literature, there are studies where models combining strategic level planning and tactical level planning are formulated for rail-based transport modes. Similar studies for Hyperloop would be beneficial in anticipating the impact of tactical-level decisions on network performance.

Another avenue of potential research is related to further validation and verification of the model. The case study employed in the study considers a limited amount of origin-destination pairs available for potential Hyperloop hubs. Due to the computational difficulties involved with increasing the number of locations selected, the findings are bound to have dependencies on the regional characteristics. Therefore, studies with more comprehensive considerations are necessary to be able to make generalized conclusions and could verify the findings of this research. The computational performance could be improved by the implementation of meta-heuristics to reach sub-optimal objectives within certain tolerances determined. Several heuristics could be compared to assess the outputted Hyperloop networks and computational performances.

7.5. Conclusion

The Hyperloop system has garnered significant attention within the European Union for its potential to revolutionize the transportation sector and promote sustainability. However, it is important to acknowledge that the technology and design of the Hyperloop are accompanied by certain ambiguities. One major hindrance in assessing the true potential of the Hyperloop lies in the absence of operational facilities dedicated to passenger transport. Without such facilities, a comprehensive evaluation of the Hyperloop's capabilities becomes challenging. Furthermore, the distinctive technological requirements of the Hyperloop necessitate the development of an entirely new and costly infrastructure. It is crucial to recognize that undertaking such projects carries inherent risks, particularly considering the substantial capital investments involved. The financial burden associated with these infrastructure endeavors renders it unlikely for the network to be reconstructed following the initial implementation. Consequently, the critical decision-making process regarding the design of the infrastructure network becomes pivotal in capturing transportation demand and ultimately facilitating a modal shift. Given the novel nature of the Hyperloop technology, uncertainties persist regarding the potential trade-offs between the network design and key performance indicators. The interplay between these factors necessitates a thorough investigation. In light of this research gap, the following research question was formulated to address these complexities and provide a deeper understanding of the subject matter.

"How does the network design of Hyperloop infrastructure with respect to varying objective criteria affect the direct and indirect impacts of the innovation?"

In order to address the research question comprehensively, a mixed research approach was employed. A thorough literature review was conducted to ascertain the current state of the Hyperloop technology and its potential for transformation within the transportation sector. Key performance indicators that contribute to a positive shift in the sector were identified and subsequently integrated into a modeling framework. The modeling framework consists of two primary stages: the demand analysis stage and the line planning stage. Within the demand analysis stage, a utility-based Multi-Nominal Logit model was adopted to construct a probabilistic mode choice model. This model was selected due to its simplicity and ability to effectively represent the decision-making process associated with mode selection. The mode attributes that contribute to the utility of a trip have been selected based on previous studies such as travel time, travel cost, number of transfers, and safety perception. The transformative potential of Hyperloop has been identified to be closely related to the lack of emissions in the operational phase, and the ability to be an attractive transportation mode that enables high-speed mobility between an origin and destination pair. Furthermore, the key performance indicators of a Hyperloop network were identified to be the modal share of Hyperloop in the market, annual revenue for the operating company, and the annually generated emissions.

Moving on to the line planning stage, a Mixed-Integer Programming (MIP) model was formulated, drawing inspiration from the Facility-Location Network Design (FL-ND) problem. This MIP model encapsulates the specific requirements of Hyperloop infrastructure. To explore the various aspects of network design, four objective functions were identified: Utility Maximization, Probability of Purchase Maximization, Emission Minimization, and Revenue Maximization. The primary objective of the formulated problem is to generate multiple Hyperloop network designs, thereby facilitating an exploration of the interplay and trade-offs inherent in network design performances. By considering these different objective functions, a comprehensive understanding of the complex dynamics involved in the design process can be obtained. The formulated model has been investigated further with a case study based in Europe. The existing European Union policies and the availability of data has resulted in the selection of 6 nodes to be considered as potential hubs: Amsterdam, Brussels, Berlin, Paris, Madrid, and Rome.

A significant conclusion drawn from the results is the notable disparities observed in the characteristics of networks generated based on different objective criteria. Notably, the Utility Maximization objective exhibits distinct behavior as indicated by the model. This objective focuses on maximizing the utility function per trip, resulting in a network design that prioritizes the establishment of direct links between potential Hyperloop hubs. This preference for direct links leads to the creation of more compact networks within origin-destination pairs, resulting in lower infrastructure costs. Interestingly, Spain and Italy are found to be of lower priority in the Utility Maximizing Hyperloop networks. Conversely, the other three objective functions yield a network design that follows a minimum-spanning tree pattern. This solution aims to ensure that passengers have access to Hyperloop transportation for every origin-destination pair. Notably, the resulting networks generated by the model, considering the objectives of the probability of purchase maximization, emission minimization, and revenue maximization, exhibit identical design patterns. Furthermore, the performance of the resulting Hyperloop networks based on the three aforementioned objective functions significantly surpasses that of the network designed with the utility maximization objective, as measured by key performance indicators. Consequently, a Hyperloop network primarily focused on utility maximization fails to attract passengers toward a modal shift, and the resulting reduction in emissions is sub-optimal. In order to maximize societal benefits, it is recommended that network designs based on the remaining three objective functions be given serious consideration. These objectives, specifically probability of purchase maximization, emission minimization, and revenue maximization, have demonstrated superior outcomes in terms of attracting passengers, achieving emission reductions, and overall economic performance. The mode choice probability findings indicate that Hyperloop becomes more competitive over trips that have longer distances.

The experiment was expanded to encompass various categories of scenarios, incorporating diversified model parameters to assess the model's sensitivity to these parameters. Three distinct categories of scenarios were established: (1) ticket price experiments, (2) safety perception experiments, and (3) policy intervention experiments. The findings from the ticket price experiments demonstrate the influence of ticket prices on the modal share of Hyperloop. Higher ticket prices are observed to discourage passengers from utilizing the Hyperloop, thereby reducing its modal share. However, it is noteworthy that the total revenue appears to remain relatively stable despite variations in ticket prices. Moreover, this study's results corroborate previous research within the literature, underscoring the significance of safety perception in the adoption of Hyperloop technology. The study identifies a critical threshold for the Hyperloop to be perceived as safe as air transport, emphasizing the importance of instilling a sense of trust and confidence among potential users. Additionally, the policy intervention experiments shed light on the supplementary role of policies aimed at discouraging short-haul flights in facilitating a modal shift towards Hyperloop. Notably, an outright ban on short-haul flights yields the highest modal share for Hyperloop, while concurrently resulting in the lowest carbon dioxide emissions. These findings collectively highlight the multifaceted factors at play in the successful implementation and adoption of Hyperloop technology. Consideration of ticket prices, safety perception, and strategic policy interventions can contribute to fostering a modal shift towards Hyperloop, ultimately promoting sustainable transportation alternatives and reducing carbon emissions.

In conclusion, this research aims to enhance our understanding of the Hyperloop system's potential in transforming the transportation sector and promoting sustainability by answering the research question generated.

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A

European Mobility Strategy and Action Plan

The European Union has identified 10 key flagship areas to devise short-term and long-term policy interventions to facilitate a more sustainable, efficient, fair, and accessible transportation sector in the region. These flagship areas are accompanied by 82 initiatives that guide the EU and its subsidiaries.

Associated Theme	Flagship
Sustainability	Boosting the uptake of zero-emission vehicles, vessels and aeroplanes, renewable & low-carbon fuels and related infrastructure
	Creating zero-emission airports and ports
	Making interurban and urban mobility healthy and sustainable
	Greening freight transport
	Pricing carbon and providing better incentives for users
Smart	Making connected and automated multimodal mobility a reality
	Boosting innovation and the use of data and artificial intelligence (AI) for smarter mobility
Resilience	Reinforce the Single Market
	Make mobility fair and just for all
	Step up transport safety and security across all modes

Table A.1: Flagships of the EU Mobility Strategy and Action Plan

The strategy outlines the vision and goals for a sustainable, connected, and efficient transportation system. The strategy aims to promote clean and digital mobility, improve connectivity, enhance passenger rights and safety, and support the development of innovative and sustainable transport solutions. The action plan sets out specific measures and initiatives to achieve these objectives. It includes investments in clean and sustainable transport infrastructure, the promotion of alternative fuels and electric vehicles, the development of smart and connected mobility solutions, and the improvement of transport networks and connectivity across Europe. The European mobility strategy and action plan also emphasize the importance of cooperation between member states, stakeholders, and industry players to achieve a coordinated and effective approach to mobility. It recognizes the need for policy alignment, research and innovation, and the active involvement of citizens in shaping the future of transportation. Overall, the European mobility strategy and action plan provide a road map for a greener, more efficient, and inclusive mobility system that meets the needs of both individuals and businesses while reducing the environmental impact of transportation. This mobility strategy serves as a basis in this study to highlight the necessity of further research toward sustainable transportation modes and supplementary policies.

B

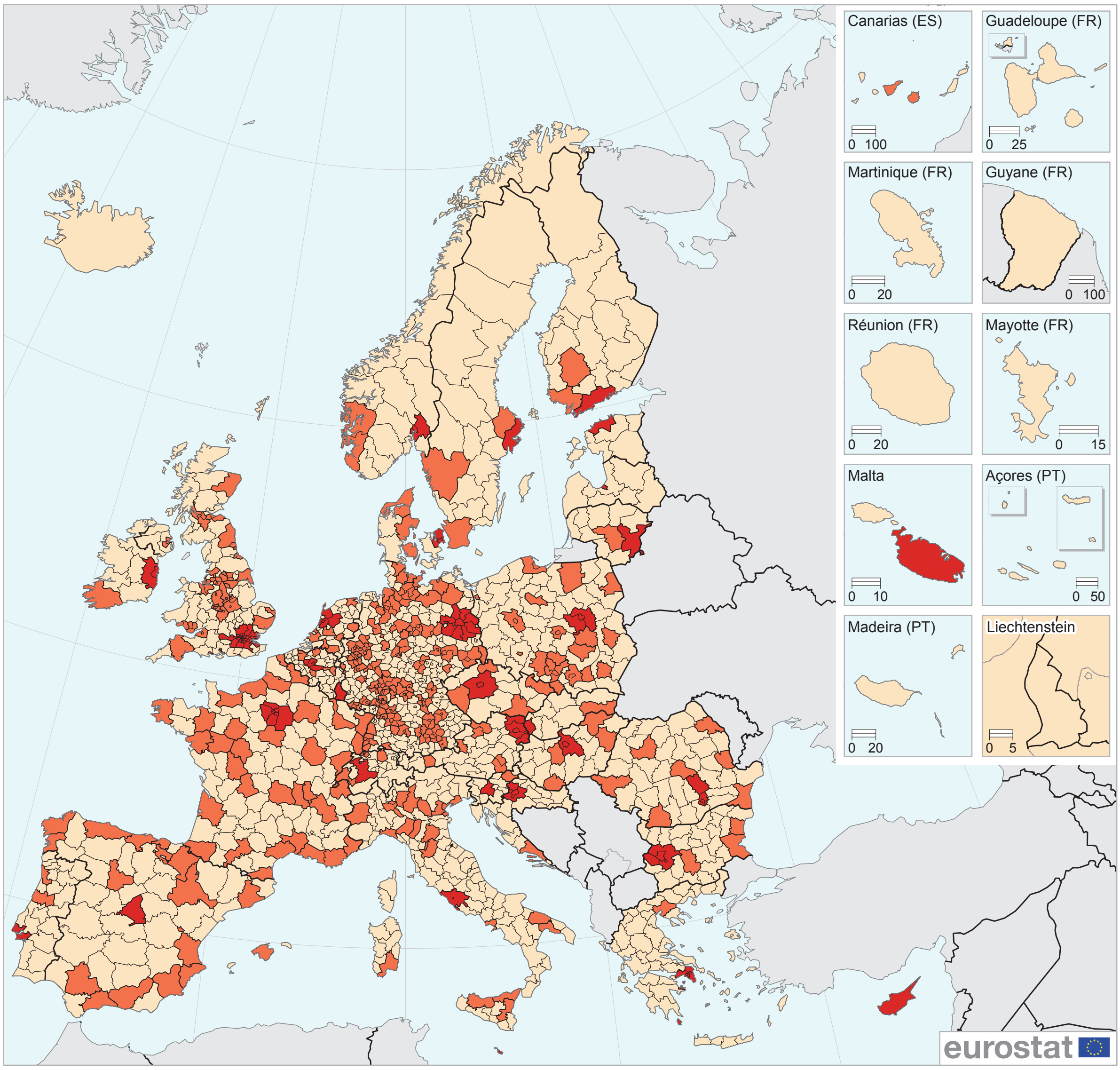
Metropolitan European Growth Areas and NUTS Regions

The Metropolitan European Growth Areas as identified by the European Union. The areas serve as a basis for the TEN-T Core Network nodes.

MEGAs are urban regions with room for demographic and economic expansion as determined by the previous studies of the European Union. MEGAs are essential for promoting sustainable development, luring investments, and stimulating innovation within their own regions and are often used as a basis for being starting points for specific policies designed for specific regions and make it easier to monitor intervention statistically and regionally. The classification of metropolitan regions serves as an important tool for anticipating the demand for more efficient and sustainable transportation services. In the European Union, these regions are given special attention as the negative externalities of sub-optimal transportation networks present the toughest challenges. Figure B.1 visualizes the MEGA classifications within Europe.

In contrast, the European Union uses the hierarchical classification system known as NUTS regions for statistical purposes. They offer a uniform framework for gathering, evaluating, and contrasting regional data between member nations. The largest geographical entities are represented by NUTS 1 regions and can be found in B.3, whereas a more general classification of NUTS 0 showcases the EU-member nations which can be seen in B.2. For the purposes of this study, MEGA and NUTS classification serves as a basis for the TEN-T network policy of the European Commission. The TEN-T network policy outlines the intentions of rail-based connectivity within Europe. Therefore, any potential Hyperloop network design could follow the guidelines and the main corridors of interest identified in TEN-T. Hence, the process could be aligned with the incremental goals of the European Union with the unified goal of providing a sustainable transport network.

Typology of metrolitan regions (at the level of NUTS 3) ([1])



Administrative boundaries: © EuroGeographics © UN-FAO © Turkstat
Cartography: Eurostat - GISCO, 08/2016

- Capital metropolitan regions
- Metropolitan regions
- Non-metro regions

0 200 400 600 800 km

([1]) Based on population grid from 2011 and NUTS 2013.
Source: Eurostat, JRC and European Commission Directorate-General for Regional Policy

Figure B.1: The Metropolitan European Growth Areas (MEGA). Source: Eurostat

Figure B.2: The Geographical scope and the countries included within the NUTS0 regional classification by Eurostat. Source: [40]

Figure B.3: The Geographical scope and the countries included within the NUTS1 regional classification by Eurostat. Source: [40]

C
Detailed Results

C.1. Ticket Price Experiments

C.1.1. Scenario T1

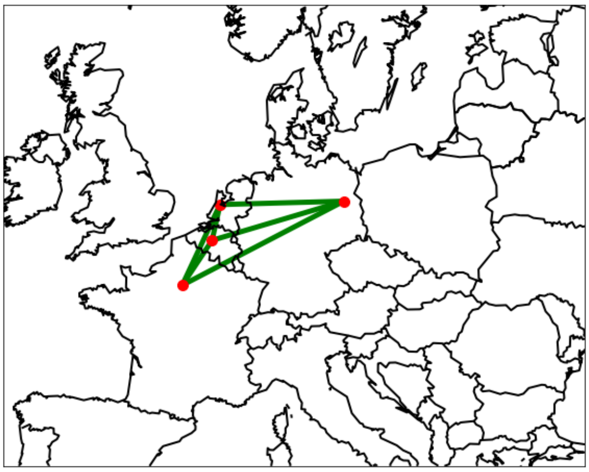


Figure C.1: The generated network for the Utility Maximization Objective in Scenario T1.

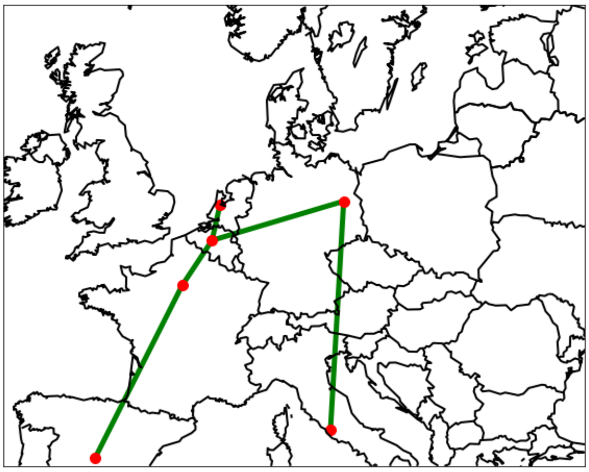


Figure C.2: The generated network for the Probability of Purchase Maximization Objective in Scenario T1.

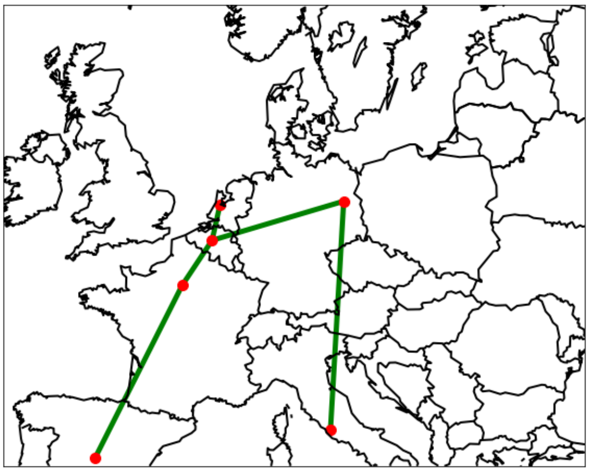


Figure C.3: The generated network for the Emission Minimization Objective in Scenario T1.

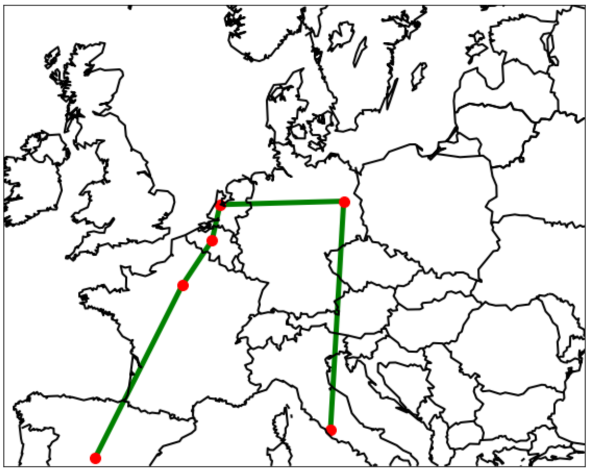


Figure C.4: The generated network for the Revenue Maximization Objective in Scenario T1.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	4	6	6	6
Number of Routes	-	6	5	5	5
Total Capital Cost	*Million €*	185989.456	186488.316	186488.316	190771.171
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	611.307	11460.283	11460.283	11460.283
Years to Break Even	-	5993	18	18	19
Total Generated Emissions	*Tons*	18394.246	4456.103	4456.103	4456.103
Modal Share of Hyperloop	*%*	15.98	58.55	58.55	58.55

Table C.1: The Key Performance Indicators of the model output with Scenario T1.

C.1.2. Scenario T3

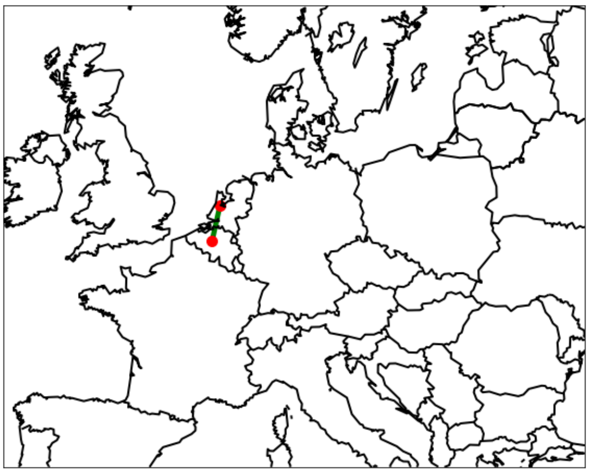


Figure C.5: The generated network for the Utility Maximization Objective in Scenario T3.

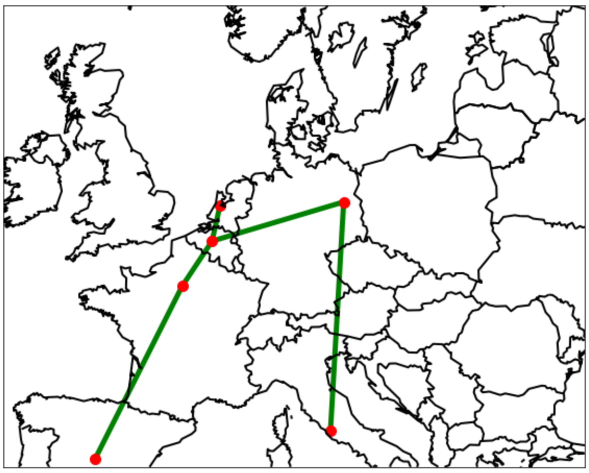


Figure C.6: The generated network for the Probability of Purchase Maximization Objective in Scenario T3.

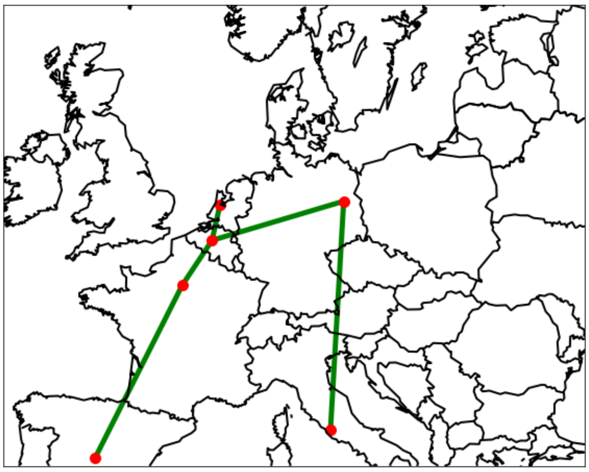


Figure C.7: The generated network for the Emission Minimization Objective in Scenario T3.

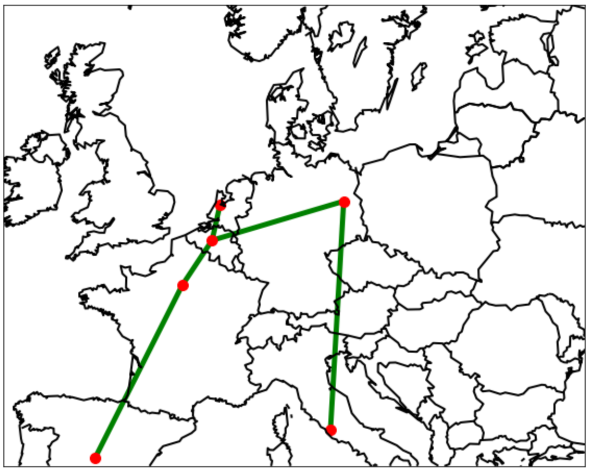


Figure C.8: The generated network for the Revenue Maximization Objective in Scenario T3.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	2	6	6	6
Number of Routes	-	1	5	5	5
Total Capital Cost	*Million €*	10428.811	186488.316	186488.316	190771.171
Annual Operation Cost	*Million €*	5.170	867.072	867.072	867.072
Annual Revenue	*Million €*	289.024	3869.871	3869.871	3869.871
Years to Break Even	-	Infeasible	63	63	63
Total Generated Emissions	*Tons*	18854.055	17033.329	17033.329	17033.329
Modal Share of Hyperloop	*%*	1.23	9.79	9.79	9.79

Table C.2: The Key Performance Indicators of the model output with Scenario T3.

C.2. Safety Perception Experiments

C.2.1. Scenario S1

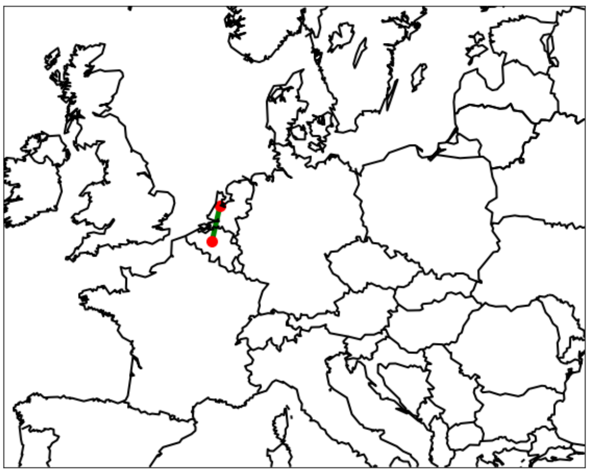


Figure C.9: The generated network for the Utility Maximization Objective in Scenario S1.

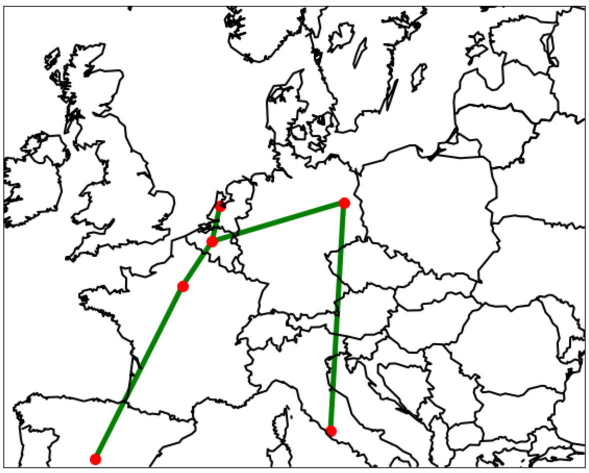


Figure C.10: The generated network for the Probability of Purchase Maximization Objective in Scenario S1.

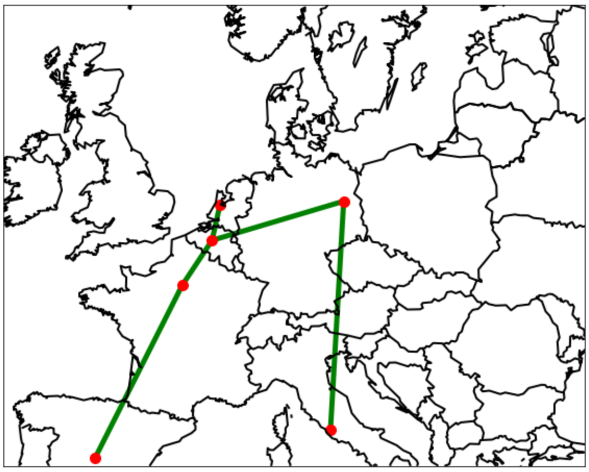


Figure C.11: The generated network for the Emission Minimization Objective in Scenario S1.

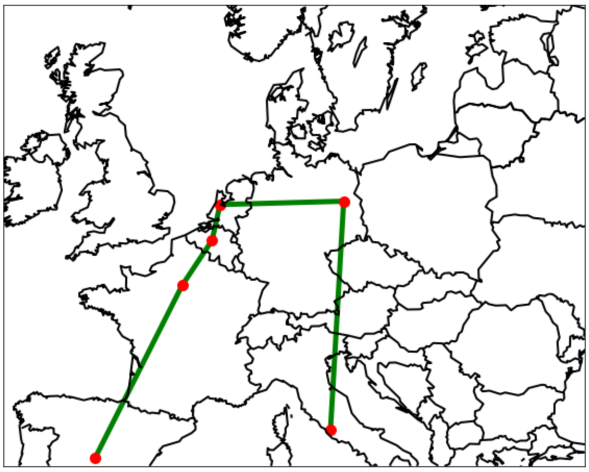


Figure C.12: The generated network for the Revenue Maximization Objective in Scenario S1.

KPIs	**Unit**	**Utility Maximization (Figure 6.7)**	**Probability Maximization (Figure 6.8)**	**Emission Minimization (Figure 6.9)**	**Revenue Maximization (Figure 6.10)**
Number of Hubs	-	2	6	6	6
Number of Routes	-	1	5	5	5
Total Capital Cost	*Million €*	10428.811	186488.316	186488.316	190771.171
Annual Operation Cost	*Million €*	5.170	867.072	867.072	867.072
Annual Revenue	*Million €*	289.024	10226.927	10226.927	10226.927
Years to Break Even	-	Infeasible	20	20	21
Total Generated Emissions	*Tons*	19210.206	11961.433	11961.433	11961.433
Modal Share of Hyperloop	*%*	0.9	26.53	26.53	26.53

Table C.3: The Key Performance Indicators of the model output with Scenario S1.

C.2.2. Scenario S3

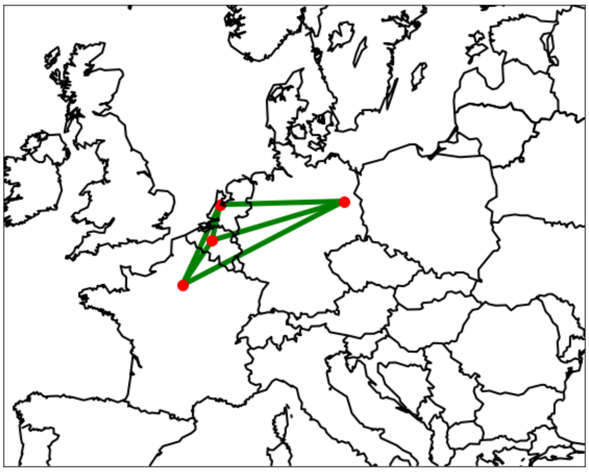


Figure C.13: The generated network for the Utility Maximization Objective in Scenario S3.

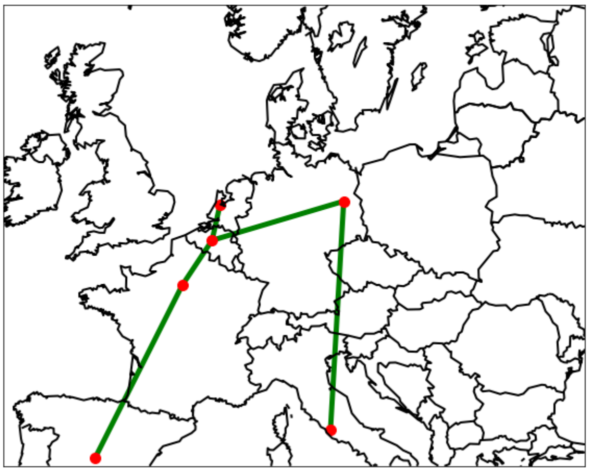


Figure C.14: The generated network for the Probability of Purchase Maximization Objective in Scenario S3.

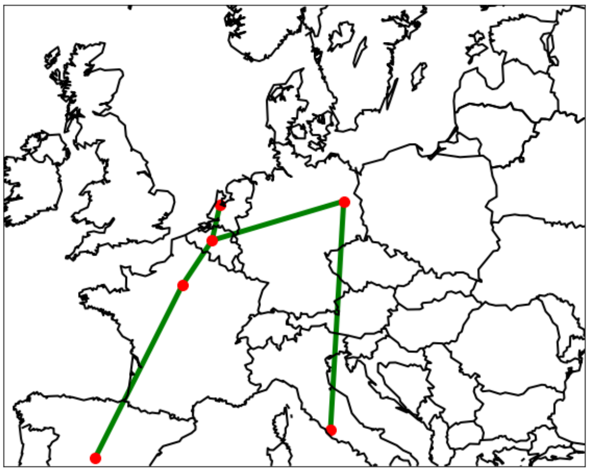


Figure C.15: The generated network for the Emission Minimization Objective in Scenario S3.

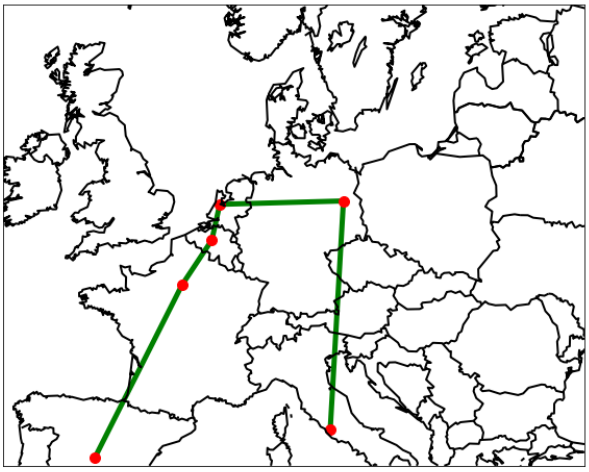


Figure C.16: The generated network for the Revenue Maximization Objective in Scenario S3.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	4	6	6	6
Number of Routes	-	6	5	5	5
Total Capital Cost	*Million €*	185989.456	186488.316	186488.316	190771.171
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	1509.274	22482.823	22482.823	22487.823
Years to Break Even	-	200	9	9	9
Total Generated Emissions	*Tons*	18324.807	4660.8669	4660.8669	4660.8669
Modal Share of Hyperloop	*%*	22.41	64.53	64.53	64.53

Table C.4: The Key Performance Indicators of the model output with Scenario S3.

C.3. Policy Intervention Experiments

C.3.1. Scenario P1

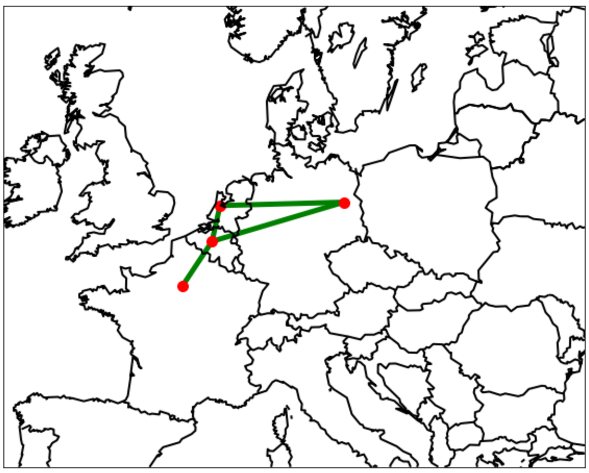


Figure C.17: The generated network for the Utility Maximization Objective in Scenario P1.

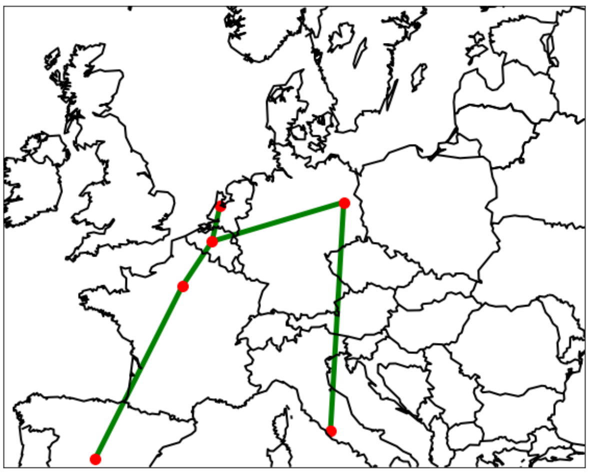


Figure C.18: The generated network for the Probability of Purchase Maximization Objective in Scenario P1.

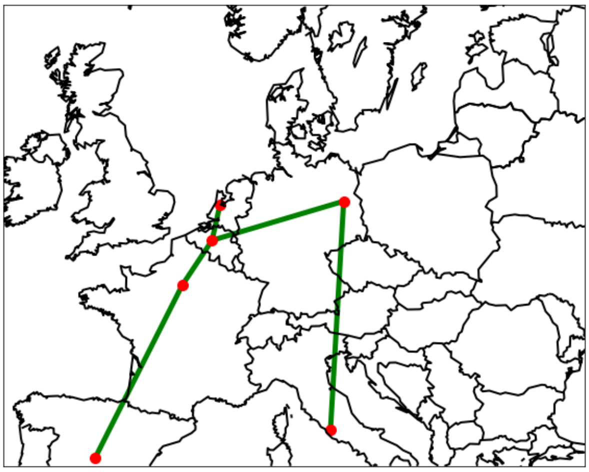


Figure C.19: The generated network for the Emission Minimization Objective in Scenario P1.

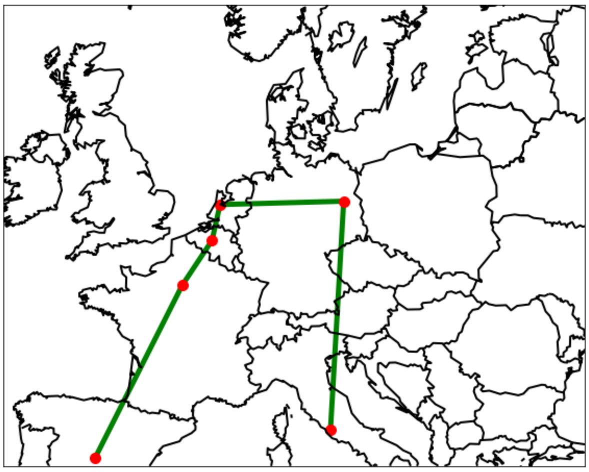


Figure C.20: The generated network for the Revenue Maximization Objective in Scenario P1.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	4	6	6	6
Number of Routes	-	4	5	5	5
Total Capital Cost	*Million €*	85201.616	186488.316	186488.316	186488.316
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	284.704	26145.875	26145.875	26145.875
Years to Break Even	-	Infeasible	8	8	8
Total Generated Emissions	*Tons*	3623.2071	2350.0695	2350.0695	2350.0695
Modal Share of Hyperloop	*%*	18.05	71.82	71.82	71.82

Table C.5: The Key Performance Indicators of the model output with Scenario P1.

C.3.2. Scenario P2

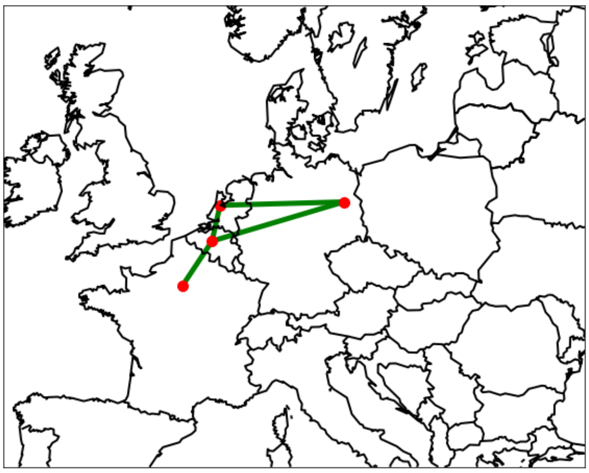


Figure C.21: The generated network for the Utility Maximization Objective in Scenario P2.

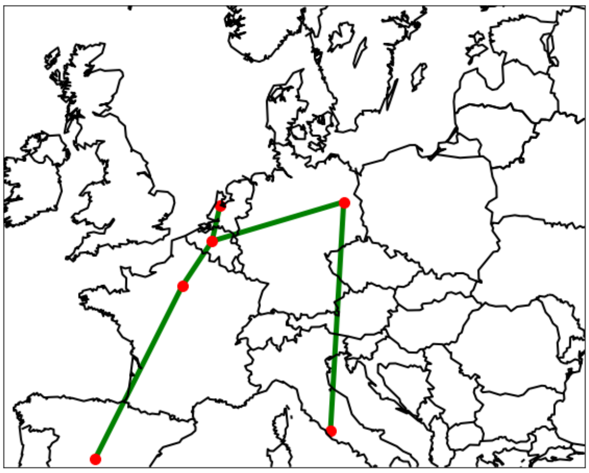


Figure C.22: The generated network for the Probability of Purchase Maximization Objective in Scenario P2.

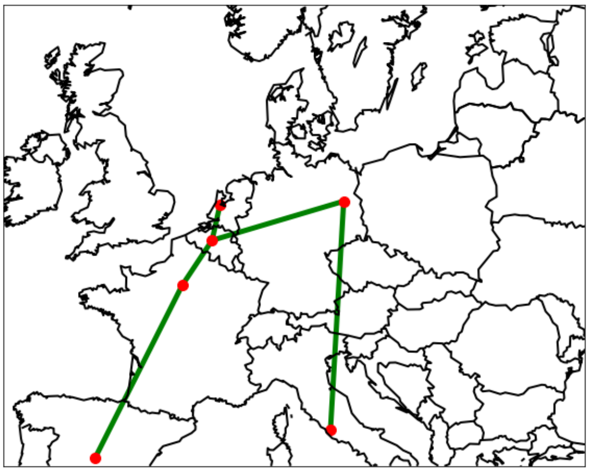


Figure C.23: The generated network for the Emission Minimization Objective in Scenario P2.

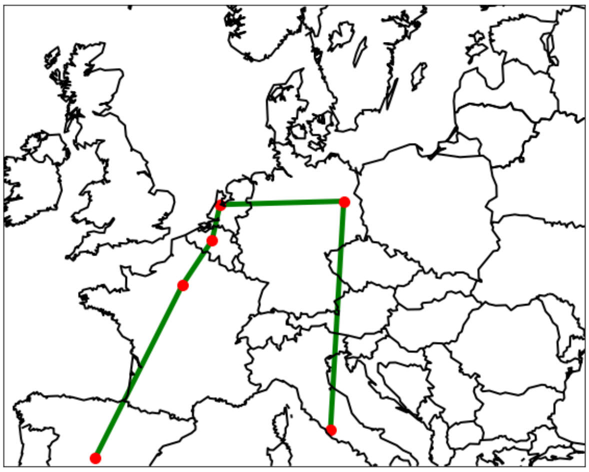


Figure C.24: The generated network for the Revenue Maximization Objective in Scenario P2.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	4	6	6	6
Number of Routes	-	4	5	5	5
Total Capital Cost	*Million €*	85201.616	186488.316	186488.316	186488.316
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	273.791	22119.508	22119.508	22119.508
Years to Break Even	-	Infeasible	9	9	9
Total Generated Emissions	*Tons*	18799.788	4490.564	4490.564	4490.564
Modal Share of Hyperloop	*%*	9.51	56.11	56.11	56.11

Table C.6: The Key Performance Indicators of the model output with Scenario P2.

C.3.3. Scenario P3

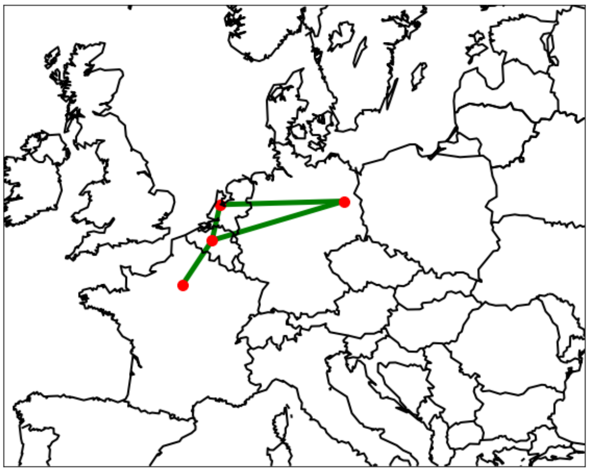


Figure C.25: The generated network for the Utility Maximization Objective in Scenario P3.

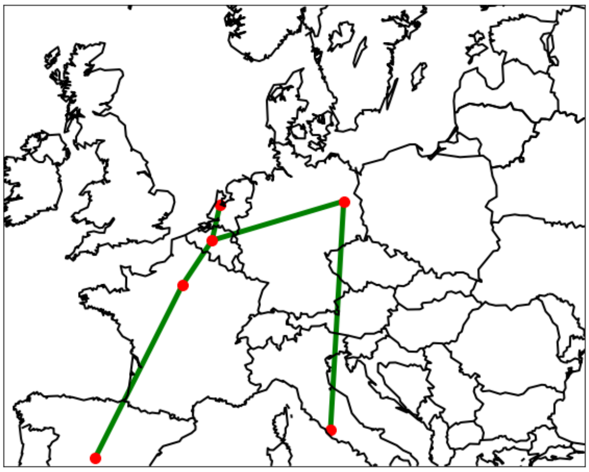


Figure C.26: The generated network for the Probability of Purchase Maximization Objective in Scenario P3.

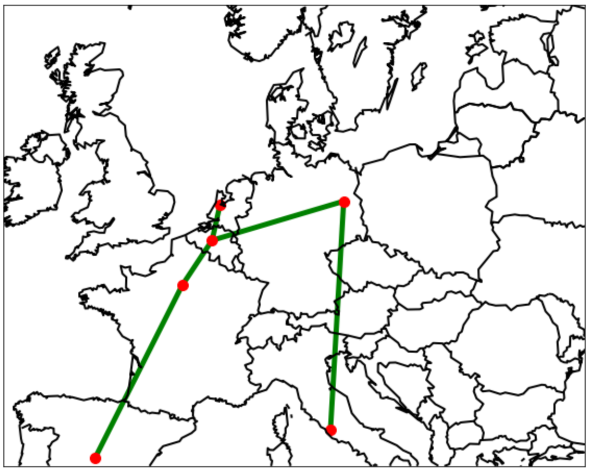


Figure C.27: The generated network for the Emission Minimization Objective in Scenario P3.

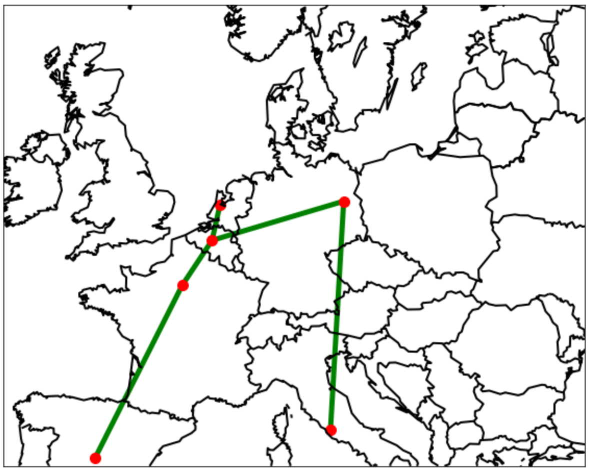


Figure C.28: The generated network for the Revenue Maximization Objective in Scenario P3.

KPIs	Unit	Utility Maximization (Figure 6.7)	Probability Maximization (Figure 6.8)	Emission Minimization (Figure 6.9)	Revenue Maximization (Figure 6.10)
Number of Hubs	-	4	6	6	6
Number of Routes	-	4	5	5	5
Total Capital Cost	*Million €*	85201.616	186488.316	186488.316	186488.316
Annual Operation Cost	*Million €*	578.048	867.072	867.072	867.072
Annual Revenue	*Million €*	371.736	20320.088	20320.088	20320.088
Years to Break Even	-	Infeasible	10	10	10
Total Generated Emissions	*Tons*	19337.152	5914.945	5914.945	5914.945
Modal Share of Hyperloop	*%*	13.64	57.36	57.36	57.36

Table C.7: The Key Performance Indicators of the model output with Scenario P3.